SEP 10 1984 S30.41:0

NAS 1.55:2325

NASA Conference Publication 2325

Geodynamics

ORIGINAL
COMPLETED

L. S. Walter
NASA Office of Space Science and Applications
Washington, D.C.

Proceedings of a workshop sponsored by the
Earth Science and Applications Division,
NASA Office of Space Science and Applications,
Washington, D.C., and held at the Airlie House
Airlie, Virginia
February 15–18, 1983

NASA

BEST COPY AVAILABLE

NASA Conference Publication 2325

Geodynamics

L. S. Walter

Proceedings of a workshop
held at the Airlie House
Airlie, Virginia
February 15-18, 1983

NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1984

BEST COPY AVAILABLE

1. M. GAPOSCHKIN. 2. P. BENDER. 3. W. CARTER. 4. J. DAVIDSON. 5. B. HAGAR. 6. W. KAULA. 7. 8. R. COATES. 9. D. TURCOTTE.
10. P. MOLNAR. 11. P. SHELUS. 12. A. ALBEE. 13. F. SPIESS. 14. N. RENZETTI. 15. J. BOSWORTH. 16. A. WATTS. 17. D. TRASK. 18. R. RAPP.
19. B. DOUGLAS. 20. A. DZIEWONSKI. 21. W. MELBOURNE. 22. W. J. MORGAN. 23. D. ANDERSON. 24. C. HARRISON. 25. W. PIOTROWSKI.
26. S. SAUNDERS. 27. W. PRESCOTT. 28. J. FANSELOW. 29. S. COHEN. 30. E. BENTON. 31. E. FLINN. 32. T. FISCHETTI. 33. K. WALLACE.
34. C. FINLEY. 35. R. LANGEL. 36. J. MARSH. 37. F. VONBUN. 38. S. HIEBER. 39. J. MURPHY.
PHOTOGRAPH TAKEN BY DAVID E. SMITH

BEST COPY AVAILABLE

Frontispiece

Photograph taken during the Geodynamics Workshop, Airlie House, VA, Feb. 15 - 18, 1983. Participants are identified in the facing diagram.

PREFACE

In 1977, NASA initiated a Geodynamics Program to continue and to emphasize solid Earth research formerly conducted as part of the Earth and Ocean Dynamics Applications Program. In 1979, a Crustal Dynamics Project was formed within the Geodynamics Program to exploit the capabilities of new positioning methods emerging from space technologies. This research is underway and is expected to continue to 1988. In addition, the Geodynamics Program is heavily involved in developing space missions and in modeling the Earth's gravity field, geoid and magnetic field as a prerequisite for studies of the solid Earth.

By 1982, it became evident that efforts underway would produce significantly important results in this decade and that the time had come to prepare for the research needs of the next decade. This Workshop was organized by NASA to solicit scientific community input as to the expected state of knowledge of the solid Earth by the 1990's and the key scientific issues which would follow. It also was intended that the Workshop identify any new technologies which would be needed to address the scientific questions of the 1990's. The Workshop participants were selected on the basis of their scientific and technical expertise. Their deliberations, conclusions and recommendations are summarized in this Conference Report.

This Report seeks to recapture the proceedings of the Workshop. It has had the benefit of several reviews by Workshop participants at various stages in its preparation. Their constructive criticisms were much appreciated and every attempt was made to include them in this report. This Report should be regarded as marking a step along the way in the process of defining the directions for the Geodynamics Program for the 1990's.

BEST COPY AVAILABLE

BLANK PAGE

TABLE OF CONTENTS

Section	Title	Page
	PREFACE	iii
I.	SUMMARY	
	A. Workshop Objectives and Participation	1
	B. Status of Space Geodynamics	1
	C. Major Scientific Questions	1
	D. Projections for Space Geodynamics	2
	E. Recommended Program Activities	4
II.	INTRODUCTION AND BACKGROUND	
	A. Introduction	7
	B. Background	7
	1. Scientific Context	7
	1.1 Definition of Geodynamics	8
	1.2 Plate Tectonics as a Framework for Modern Research	8
	1.3 Crustal Movement and Deformation	8
	1.4 Polar Motion and Earth Rotation	8
	1.5 Gravity and Magnetic Fields	9
	1.6 Important Scientific Questions	9
	1.7 Practical Aspects	10
	1.8 Limitations of Ground-Based Data	11
	2. NASA Geodynamics Program	12
	2.1 Objectives and Structure	12
	2.2 Federal Coordination	12
	2.3 International Coordination	13
	2.4 Crustal Dynamics Project	13
	C. Status of Space Geodynamics, Current and Future	14
	1. Geodetic Measurements	14
	1.1 Techniques	14
	1.2 Results	17
	2. Global Dynamics Measurements	21
	3. Geopotential Fields	21
III.	PROJECTIONS FOR SPACE GEODYNAMICS, 1988-1998	
	A. Premises	27
	B. Results of Panel Discussions	28
	1. Geopotential Fields	28
	1.1 Dynamics and Structure of Continents	28
	1.2 Dynamics of the Sub-Oceanic Crust and Lithosphere	29
	1.3 The Deep Interior	29
	1.4 Related Applications	31
	1.5 Future Missions and Studies	31
	1.6 The Planets	32

BEST COPY AVAILABLE

2. Global Dynamics.....34
2.1 Earth Rotation and Polar Motion.....34
2.2 Mission to Map the Time-Varying Field.....34
2.3 Ground-Based Measurements.....36
3. Tectonics.....37
3.1 Geodetic Measurements.....38
3.2 Gravity Data.....40
3.3 Information/Measurement Requirements.....40
4. Regional Tectonics - Crustal Hazards.....41
4.1 Regions of Interest.....41
4.2 Observational Program Requirements - Western U.S.....43

IV. RECOMMENDED PROGRAM ACTIVITIES - 1988-1998

A. Ground-Based Observations.....45
B. Space Missions.....46
C. Instrument Development.....48
D. Ancillary Measurements and Supporting Activities.....48

APPENDIX I Geodynamics Workshop Attendees.....I-1

APPENDIX II Geodynamics Worksho, Agenda.....II-1

BEST COPY AVAILABLE

LIST OF FIGURES

Number	Title	Page
	Group Photograph	Frontispiece
1	GPS Geodetic Receivers	16
2	Crustal Dynamics Project Sites	18
3	The Geopotential Research Mission	23
4	Continent-Continent Collision	24
5	The Kentucky Anomaly	25
6	Superconducting Gravity Gradiometer	33
7	Change in Length of Day	35
8	Concepts for Monitoring Ocean Floor Spreading	47

LIST OF TABLES

Number	Title	Page
1	Preliminary Observations of Tectonic Plate Movement	17
2	Accuracy Estimates for 400 km Baselines	42

BEST COPY AVAILABLE

I. SUMMARY

A. Workshop Objectives and Participation

The Geodynamics Workshop held at the Airlie House, Airlie, Virginia, in February 1983 was sponsored by the Earth Science and Applications Division of the Office of Space Science and Applications, National Aeronautics and Space Administration. The objectives of the Workshop were to: (1) evaluate the scientific and technological progress achieved by the Geodynamics Program by 1988, and (2) recommend activities needed to address important geodynamic research needs of the next decade. The Workshop was attended by 60 scientists and technical managers from universities, research institutions, NASA Headquarters and Centers, and other government agencies.

B. Status of Space Geodynamics

The Workshop participants reviewed and discussed the status and accomplishments of space geodynamics projected to the year 1988. These included the expected achievements in measuring contemporaneous relative motions of several of the major plates (North American - Pacific, Nazca -South American, North American - Eurasian); epoch measurements of other plate combinations (Aegean - Eurasian, Caribbean - North American - South American) and determination of strain accumulation rate in the western U.S. It also included dramatic improvement in the ability to measure polar motion and changes in the length of day and the correlation of these phenomena with geophysical phenomena such as changes in average zonal wind and mean sea level, redistributions of the Earth's mass, and coupling of fluid motion of the core to the mantle. In addition, significant results will have been achieved in the analysis of the Earth's gravity and magnetic fields.

C. Major Scientific Questions

As a result of the discussions and deliberations of the Workshop, the participants believed that the major questions facing geodynamics in the 1990s would include the following:

- What is the origin of the geomagnetic field?
- What is the cause of both the gradual and sudden changes in this field?
- How is the Earth's angular momentum partitioned between the core, crust, oceans and atmosphere, and what are the mechanisms governing the angular momentum transfer?
- What can variations in the gravity field tell us about the dynamics of the solid Earth?

BEST COPY AVAILABLE

- What is the nature of convection in the Earth's mantle and how is this related to the forces which drive the plates?
- What combinations of forces drive the plates?
- Is the contemporary rate of plate motion constant?
- To what extent can individual plates by considered to be rigid bodies?
- What is the rate and mechanism of separation at sub-oceanic spreading centers?
- How do these compare with the rates and mechanisms of subduction, collision of plates and rifting of continental crusts?
- How do plates deform near active boundaries and how is this deformation related to earthquakes?

What these questions have in common is that space observations of the gravity and magnetic fields and space geodesy can make important contributions toward their eventual solution.

D. Projections for Space Geodynamics

The Workshop participants strongly recommended that the NASA Geodynamics Program continue through the decade of the 1990s. The Program should concentrate on activities that are directed toward answering fundamental scientific as well as practical questions relating to earthquake prediction, geodetic measurement techniques and petroleum and mineral exploration. The Workshop participants assumed that, by the end of this decade, the Geopotential Research Mission (GRM) will have been launched and that, through the Crustal Dynamics Project, the capability for one-centimeter position determinations would have been achieved and applied to the determination of the relative motions and internal deformation of several of the major plates. On this basis, a number of high-priority needs for observations during the next decade were identified:

- <u>Geopotential Fields</u>

  1. Global, long-term mapping of the Earth's magnetic field for modelling the dynamo source and its variations;
  2. High resolution gravity field data (on the order of one milligal at ultimate spatial resolution of 25 km) for studies of tectonic mechanisms;

BEST COPY AVAILABLE

3. More accurate mapping of the long-wavelength component of the gravity field for studies of the structure and dynamics of the deep mantle; and

4. Global topographic data at the level of precision of five meters to be used in model development in conjunction with gravity and magnetic field data.

- Global Dynamics

1. Time-variant global gravity data for precise determination of terrestrial harmonic coefficients. This data will provide information related to post-glacial rebound and seasonal movement of water, and hence, the physical properties of the crust and mantle.

2. A program of frequent (e.g., daily or shorter) and precise (milliarcsecond or better) determination of nutation, polar motion and earth rotation rate carried out for at least several years for assessment of the structure and properties of the core and the cause of phenomena such as the Chandler wobble and its relationship to great earthquakes and atmospheric phenomena. Investigation of the Earth's angular momentum budget and the related exchanges between the atmosphere, ocean, crust, mantle, and core.

- Tectonics

1. Continued geodetic baseline measurements at the level of accuracy of one centimeter to assess contemporary variations in the rates of plate motions, the variation of motion across plate boundaries and the motion across zones of convergence and divergence;

2. Measurement of sub-oceanic convergence at subduction zones, divergence at spreading centers, and displacements across transform faults;

3. The determination of vertical motions on short baselines to study earthquake and mountain-building processes and on longer baselines to study post-glacial adjustment.

- Regional Tectonics/Crustal Hazards

1. Frequent, accurate baseline determinations of generally closely spaced arrays of points for determination of secular strain accumulation patterns for co- and post-seismic studies of deformation and to support efforts in earthquake prediction.

BEST COPY AVAILABLE

E. Recommended Program Activities

To satisfy the stated observational requirements, the following activities, not necessarily in order of priority, were recommended for the Geodynamics Program beyond 1988:

1. Conduct a mission to monitor the main magnetic field, launched at a magnetically quiet period with sufficient lifetime to capture sudden changes in the direction and strength of the field;

2. Develop a magnetic gradiometer and test on a tether or on an available free flyer;

3. Develop a gravity gradiometer and launch it aboard a low-orbiting free flyer;

4. Launch a laser retroflecting satellite in an orbit which would be sensitive to the long-wavelength component of the gravity field to improve the determination primarily of low-order harmonics (e.g., 5-12) of the gravity field. This requirement is contingent upon the orbit error characteristics of GRM.

5. Use data available from synthetic aperture radars and the Large Format Camera, in combination with data from an appropriate microwave altimeter, for global topographic mapping to aid in interpretation of gravity models;

6. Develop an improved position measurement capability through the use of reference frames provided by earth-orbiting satellite- and lunar- laser ranging and astronomical sources;

7. Continue deployment and use of existing ground-based equipment in measurement campaigns and coordinate these activities with those of U.S. operational agencies and international programs;

8. Develop the capability for accurately (5 centimeter) relating sea-floor positions to one another and to points on land;

9. Develop the capability for precise (in the range of several millimeters) determination of change in the vertical vectors of baselines from tens to hundreds of kilometers;

10. Develop improved systems for position determination at the 1-cm level utilizing satellites in high stable orbits which may be accurately determined. This development should examine:

    - both laser and radio tracking systems, and

    - both NAVSTAR and alternative spacecraft systems with a view toward obtaining the requisite precision and mobility in the most cost-effective manner.

BEST COPY AVAILABLE

11. Develop a Satellite-borne Laser Ranging System (SLRS) for high-density regional position determinations using ground-based corner cube reflectors.

BEST COPY AVAILABLE

BLANK PAGE

II. INTRODUCTION AND BACKGROUND

A. Introduction

This document summarizes the discussions, results and recommendations of the Geodynamics Workshop which was held at the Airlie House, Airlie, Virginia in February 1983. The Workshop had two objectives: (1) to evaluate the scientific and technological progress expected to be achieved in NASA's Geodynamics Program by 1988, and (2) to recommend activities needed to address the important geodynamics research needs of the next decade.

The meeting was attended by 60 scientists and technical managers. Approximately one-third of these were from universities and research institutions; one-third from NASA Centers and one-tenth each from NASA Headquarters and other government agencies. Appendix 1 lists the attendees.

The group met for four days and discussed the current and projected status of the major scientific questions confronting geodynamics as well as the space technology which could be applied to these problems. Programmatic considerations, including relationships with other programs, were also discussed. Possible major thrusts were defined by individual panels (Tectonics, Crustal Hazards, Solid Body Dynamics and Potential Fields) and these results were reviewed by the Workshop as a whole. (The agenda of the meeting is presented in Appendix 2).

This Report parallels the presentations and discussions which took place at the meeting. The remainder of Section II provides an overview of the field of geodynamics and its major scientific questions. It also describes the current NASA Geodynamics Program, its current status and the projected accomplishments by the year 1988.

Section III presents the results of the discussions of the four Working Groups at the meeting, identifying the significant scientific questions anticipated in these sub-disciplines and the observational requirements required to help provide answers to these questions.

Section IV first considers the observations needed from the standpoint of measurement programs. It then presents the new technologies which must be developed and the flight missions which must be carried out in order to meet these measurement objectives.

B. Background

1. Scientific Context

The scientific context of the meeting was based on the following definitions and framework:

BEST COPY AVAILABLE

1.1 Definition of Geodynamics

Geodynamics is the study of the dynamics of the Earth. It is the branch of science which deals with the physical forces and processes (both internal and external) which affect the solid Earth and core. Geodynamics includes the study of the Earth's structure and dynamic motion and how these relate to the following: the structure, composition, evolution and deformation of the solid Earth; the Earth's magnetic and gravity fields and the processes which generate them; solid Earth and ocean tides and time variations in the Earth's rotation and the orientation of its rotational axis.

1.2 Plate Tectonics as a Framework for Modern Research

One of the fundamental theoretical frameworks in which geodynamics studies are conducted is plate tectonics. The theory of plate tectonics describes the lithosphere as being divided into approximately 20 blocks, called "plates", which, to a first approximation, are rigid. The plates move slowly (1-10 cm/yr) in response to driving forces which result from phenomena occuring in the Earth's interior. While these motions are slow on human time scales, the effects are impressive. Most of the world's mountain ranges, ocean deeps, great earthquakes and volcanic activity are associated with the relative motions of these plates where they (1) slide horizontally past each other, as in California; (2) are forced over or under one another, as in the Andean region and the Aleutian trench and island arc; (3) collide as in the Himalayas; or (4) are separating, as in the East Pacific Rise.

1.3 Crustal Movement and Deformation

It is apparent however, that the assumption of plate rigidity is not strictly valid. This is a fact made evident by the considerable seismicity and mountain building at significant distances from plate margins, as in the Basin and Range of the western U.S. Indeed, the plates, far from being rigid, are the sites of abundant tectonic and magmatic activity as evidenced by intra-plate faulting (e.g., the Rocky Mountains) and volcanism (e.g., the Hawaiian Islands and Yellowstone). It is believed that the plates deform significantly at plate margins as the relative movement between adjacent plates is distributed in the bordering zones.

1.4 Polar Motion and Earth Rotation

It has long been known that the position of the Earth's pole and the rate of rotation about its axis change in response to dynamic phenomena both on and in the Earth. Although the motions are far from being completely understood, recent improvements in the ability to measure the parameters related to the Earth's orientation in space as well as in our understanding of the basic model of the Earth's structure have enabled a better understanding of the phenomena. Variations in these quantities on the time scale of a decade and longer (up to a few thousand years)

BEST COPY AVAILABLE

are considered to be primarily due to changes in the mass distribution of the Earth's interior (except during periods of rapid glaciation change). At the other end of the frequency spectrum, variations on the order of days to a few years have been shown to be related to changes in the angular momentum and mass distribution of the atmosphere.

1.5 Gravity and Magnetic Fields

Changes in the gravity field were not observed on the global scale until very recently. Even given the measurement sensitivity of space techniques, it is unlikely that such data will soon become available for any terms beyond those of low degree. However, the static gravity field is of importance in geodynamics because perceptible motions may be the result of isostatic disequilibrium (e.g., the rebound following deglaciation). Alternatively, tectonic movement often results in observed variations in the short wavelength gravity anomalies (as in back-arc basins).

Centuries of experience with the use of magnetic fields for navigation have demonstrated that this geopotential field is not static. Its intensity changes on the order of 0.1 percent per year and recent data indicate that sudden changes in the position of the pole may occur much more rapidly than that. As with the motion of the rotational pole, secular changes in the Earth's magnetic field take place on a variety of time scales. Wandering of the magnetic pole is observed on short (10^3-year), and reversals in the polarity of the field have reoccurred more or less regularly, on much longer ($>10^5$-year) time scales.

1.6 Important Scientific Questions

Observations and measurements of these phenomena (crustal and plate motion, polar motion, earth rotation and geopotential fields) are made by geodesists and geophysicists to answer fundamental questions concerning the evolution, dynamics and nature of the Earth. Among these questions are:

What are the forces which drive the motion of the tectonic plates?

- To what degree do the plates behave non-rigidly?
- Are the rates of plate motion and strain accumulation nearly uniform with time or are the movements episodic?
- How does the relative motion between adjacent plates affect the plate interiors? What is the degree of strain at plate boundaries?

What constraints does post-glacial rebound provide on mantle viscosity and its variation with depth?

BEST COPY AVAILABLE

What is the nature of material in the Earth's mantle (i.e., the details of convection)?

- How does mantle convection relate to geophysical, geological and geochemical phenomena at the surface of the Earth?

What is the structure of the core and what is the nature of the dynamics of motion of the fluid core?

- What is the origin of the Earth's magnetic field?
- What is the cause of the secular variation in this field?
- What causes the rapid reversals in polarity?
- Are motions in the fluid core coupled to the mantle? Are such motions responsible for variations in the rate of rotation of the Earth?

What are the various causes in the excitation of the Earth's rotation? What are the roles and what are the interactions between the various components in the Earth's angular momentum budget (e.g., atmosphere, ocean, core, and mantle)?

- How do atmospheric winds, the water budget, and earthquakes affect Earth orientation?
- What mechanisms are involved?

1.7 Practical Aspects

Along with the desire to understand the fundamental processes operating within the Earth, studies in geodynamics also contribute to practical applications.

It is accepted that earthquakes are related to the movement of tectonic plates. Seismic events are mainly the result of a sudden release of strain within the boundary zones between plates. Thus, the studies of the motions, and especially the accumulation of strain at boundaries, are fundamental to the understanding of earthquake mechanisms. Such studies may eventually contribute to the development of the ability to predict earthquakes.

Other hazardous natural phenomena are also, though less directly, related to the dynamics of the crust and the mantle. Volcanic eruptions are the result of upwellings of magma generated where mantle plumes cause "hot spots" or where subduction of a plate results in partial melting of water-bearing rocks exposed to high temperatures and pressures.

BEST COPY AVAILABLE

Even meteorological hazards may be linked to geodynamic studies, though still less directly. It has been demonstrated that variations in the distribution of the angular momentum of the atmosphere are very highly correlated to the changes in the rotation rate of the Earth (the length of day) for periods less than two years. Discernable changes in the rotation rate have a seasonal structure. Changes on the time scale of decades could be linked with magnetic field variations within the fluid core.

In the area of resource exploration, investigations on the structure and dynamics of the mantle lead to improved understanding of processes such as sedimentation, the generation and emplacement of magmas and the formation of mineral deposits.

An accurate knowledge of the gravity field and geoid is important for determination of satellite orbits and missile trajectories and to studies of global ocean circulation. Similarly, accurate models of the magnetic field are needed for the production of magnetic field charts and maps for navigation.

Finally, since many of the measurements of baselines and gravity field are the same, geodynamics studies contribute directly to (and draw directly from) activities in the field of geodetic surveying.

1.8 Limitations of Ground-Based Data

The most accurate line-of-sight baseline length measurements can achieve levels of about 2 parts in 10^7 up to distances of 30 km. Such measurements on networks of lines crossing the major U.S. seismic zones are very valuable for monitoring accurately the accumulation of strain near major fault systems. The accuracy for measuring height differences over similiar distances by leveling is also below 1 cm in fairly level areas but somewhat worse in mountainous areas. However, first-order leveling is very expensive and quite time-consuming.

Space techniques, on the other hand, are more accurate over distances greater than 100 km. All three components of baselines are determined at the same time, and the cost can be considerably less than for leveling alone. Such measurements are complimentary to more detailed ground measurements close to faults, since they add the longer wavelength information on the overall strain accumulation pattern. Also, space techniques soon will make possible less expensive and therefore more frequent measurements than for ground techniques over shorter distances near faults, which will be valuable in looking for possible accelerated strain accumulation rates just before large earthquakes. Space techniques are of course much more accurate than measurements by ground techniques over distances considerably larger than 100 km, and are the only feasible way to study present plate tectonic motions over longer distances.

BEST COPY AVAILABLE

2. NASA Geodynamics Program

Because of the need for precise geodetic and geopotential data and in view of the potential of satellite technology in satisfying these needs, NASA responded, over a decade ago, with the formation of the Geodynamics Program.

2.1 Objectives and Structure

The objectives of the Geodynamics Program are:

- To contribute to the understanding of the solid Earth; in particular, the processes that result in movement and deformation of the tectonic plates;
- To improve measurements of the Earth's rotational dynamics and its gravity and magnetic fields in order to better understand the internal dynamics of the Earth.

The Program supports the development of new instrumentation and space missions in order to facilitate the improvement of precise measuring systems by which the above phenomena may be assessed. It is subdivided into three areas:

Crustal Dynamics Program - performs field measurements and modeling studies relative to crustal deformation in various tectonic settings;

Geopotential Research Program - uses space and ground measurements to better describe the gravity and magnetic fields; investigates data analysis techniques and software systems; and

Earth Dynamics Program - measures and models polar motion and earth rotation and relates studies of global plate motion to the dynamics of the Earth's interior.

2.2 Federal Coordination

Geodynamics is an interdisciplinary earth science. Several federal agencies are involved in research in one or more aspects of this field. Since space technology is only one of the possible tools for advancing the understanding of the solid Earth, NASA has sought a close working relationship with the other relevant federal agencies.

In September 1980, an Interagency Agreement involving NASA, NOAA, USGS, DMA and NSF established provisions for overseeing the development of space technology for crustal dynamics and earthquake research. The Agreement set up a Program Review Board and an Interagency Coordinating Committee and led to the development of a Federal Implementation Plan for the joint development and use of space systems for the acquisition and analysis of data, for the transition of new technologies from R&D to operational status and for expansion of the national effort to a global program of geodynamics research. Specifically, three new services are

BEST COPY AVAILABLE

planned: (1) a National Crustal Motion Network by NOAA beginning in 1984; (2) an improved Polar Motion and Earth Rotation Service (POLARIS) jointly developed by NASA and NOAA and operational in 1983; and (3) a Local Crustal Motion Network based on the use of the DOD Global Positioning System (GPS) satellites.

In view of the importance of GPS to civilian geodesy, an interagency group including NOAA, DOD, NASA and USGS prepared a plan for the development and testing of GPS receiver concepts. This plan provides a basis for coordination of the activities of these federal agencies for testing and eventually selecting the optimum GPS positioning method based on costs and performance for federal use.

2.3 International Coordination

Tectonic plate motion, polar motion and Earth rotation are being monitored in 20 countries in coordination with the NASA Geodynamics Program. These countries include the Federal Republic of Germany, the Netherlands, France, Great Britain, Greece, Austria, Spain, Sweden, Italy, Australia, Japan, Canada and China. Others are participating through Principal Investigators and, generally through the Investigators, by providing sites for measurements. International scientific groups, such as the IUGG and IAU are also active in these coordinated projects.

2.4 Crustal Dynamics Project

The Crustal Dynamics Project was established by NASA in 1979 to apply space technology to advance the scientific understanding of crustal movement and deformation and earthquake mechanisms. It is managed by the Goddard Space Flight Center and will continue through 1988.

The objectives of the Project are to measure and model: regional deformation and strain changes related to earthquakes at the plate boundary in the Western US and Alaska; the present relative velocities of major plates with emphasis on the North American and Pacific Plates; internal deformation of the North American and Pacific Plates and regional deformation in areas in which the tectonic setting is similar to that of the western U.S. and Alaska.

The measurement techniques developed and used by the Project include Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR) and Very Long Baseline Interferometry (VLBI) (using astronomical radio sources). Data products include time series of the observing site locations, baseline lengths and directions, and polar motion and earth rotation. Accuracies of a few centimeters over baseline lengths of up to several thousand kilometers, and baseline length changes of one to two centimeters per year, are expected.

BEST COPY AVAILABLE

C. Status of Space Geodynamics, Current and Future

1. Geodetic Measurements

1.1 Techniques

Under the Crustal Dynamics Program, several techniques have been, and continue to be, developed to levels of precision and accuracy never before achieved; levels which are required in order to measure the movement and possible distortion of the tectonic plates. The techniques can be divided into two categories: laser ranging and microwave interferometry and ranging.

In laser ranging, pulses from the laser are transmitted to, and reflected from, corner-cube reflectors located on a satellite or on the moon and finally detected through a receiving telescope. The distance to the reflector is calculated using the measured time interval and the known velocity of light. Satellite Laser Ranging (SLR) uses reflectors on artificial satellites. The principal satellites used for this purpose are LAGEOS, Starlette and Beacon-Explorer-C. Lunar Laser Ranging (LLR) uses reflectors that have been emplaced on the lunar surface.

The Crustal Dynamics Project obtains data from 17 laser stations which are more or less permanently located: five on the North American plate, three on the Pacific plate, two in Australia, six on the Eurasian plate and one in South America. In addition, two transportable laser ranging stations are currently available. These currently move at intervals of one or two months among sites where important measurements are made for regional tectonic studies. In 1983, the two available mobile stations will visit seven different sites. Shorter measurement times per site are expected as orbit model errors are reduced.

The geodetic precision of SLR measurements is a function of the length of the baseline being determined. In the case of shorter baselines, where measurements can be made simultaneously from two or more ranging stations, the major error sources are due to instrumental error, gravity field models, atmospheric corrections, along-track changes in acceleration and ocean tides. RMS errors are less than two centimeters. Longer baseline determinations (over 4000 km) are sensitive to essentially the same error sources, but the effects of the last three are substantially increased. In this case, which includes errors due to Earth rotation and polar motion, errors are currently on the order of five centimeters.

In Very Long Baseline Interferometry (VLBI), radio signals from astronomical radio sources are recorded simultaneously at two or more ground stations. The difference in arrival times (group delay) is determined by cross-correlation of two such recordings; this group delay is proportional to the component of the baseline between the two stations in the direction of the astronomical source. The baseline is then estimated from approximately 100 group delays, measured over a time span of about 24 hours.

BEST COPY AVAILABLE

Permanent stations from which the Crustal Dynamics Project obtains VLBI data are located in North America (five sites), on the Pacific plate (one site) and on the Eurasian plate (two sites). Mobile VLBI systems have been developed which can visit and make measurements from new sites in one or two days. In 1983, the two available mobile VLBI systems will visit 18 different sites for regional deformation measurements.

The accuracy of VLBI measurements is also a function of baseline length. The main sources of error are instrument noise and atmospheric effects although Universal Time and polar motion are important sources in errors in the transverse components of the baselines. At 400-kilometer baseline length, these limit precision in length to about 1.5 centimeters (RSS) and at 4000 kilometers, to about 2.5 centimeters. For baselines of 400-kilometers length, the accuracy of the transverse horizontal component is approximately equal to that for the length; the accuracy of the baseline vertical component is worse by a factor of about three, primarily because of atmospheric effects.

In order to detect systematic errors in SLR and VLBI techniques and to determine accuracy, campaigns are periodically carried out in which measurements from the two types of systems are made nearly simultaneously along the same baselines. In such cases, the difference in baseline length using the two methods is one to ten centimeters. So far, one major error source, external to the systems, lies in the determination of the relative positions of the SLR and VLBI sites at either end of the baseline. Thus, the agreement and absolute accuracy may be better than the apparent differences indicate.

Future SLR capability will be augmented through the addition of two mobile systems which would permit occupation of up to 24 mobile sites a year, even with observation times of two months per site. (Observation strategies, however, occasionally require residence at one site for up to four months so the actual total may be somewhat less). Project objectives call for the precision of these measurements (over periods of years using the same techniques but, sometimes in changed instrument configurations) to be one centimeter.

Several fixed VLBI stations are scheduled to be added: two in North America, three in South America, two on the Pacific plate and one on the Eurasian plate. In the case of VLBI measurements as well, Project objectives call for precision of one centimeter.

In addition, a new technique will be employed which makes use of the Department of Defense's Global Positioning System (GPS). The constellation of NAVSTAR (GPS) satellites (of which six are in place and a total of 18 are projected by 1988) transmit radio signals which permit a pair of ground receivers to locate their relative positions. Due to the strength and relative proximity of these sources, the receivers can be small and inexpensive compared with current VLBI instruments while achieving comparable precision at least for short baselines (Figure 1).

BEST COPY AVAILABLE

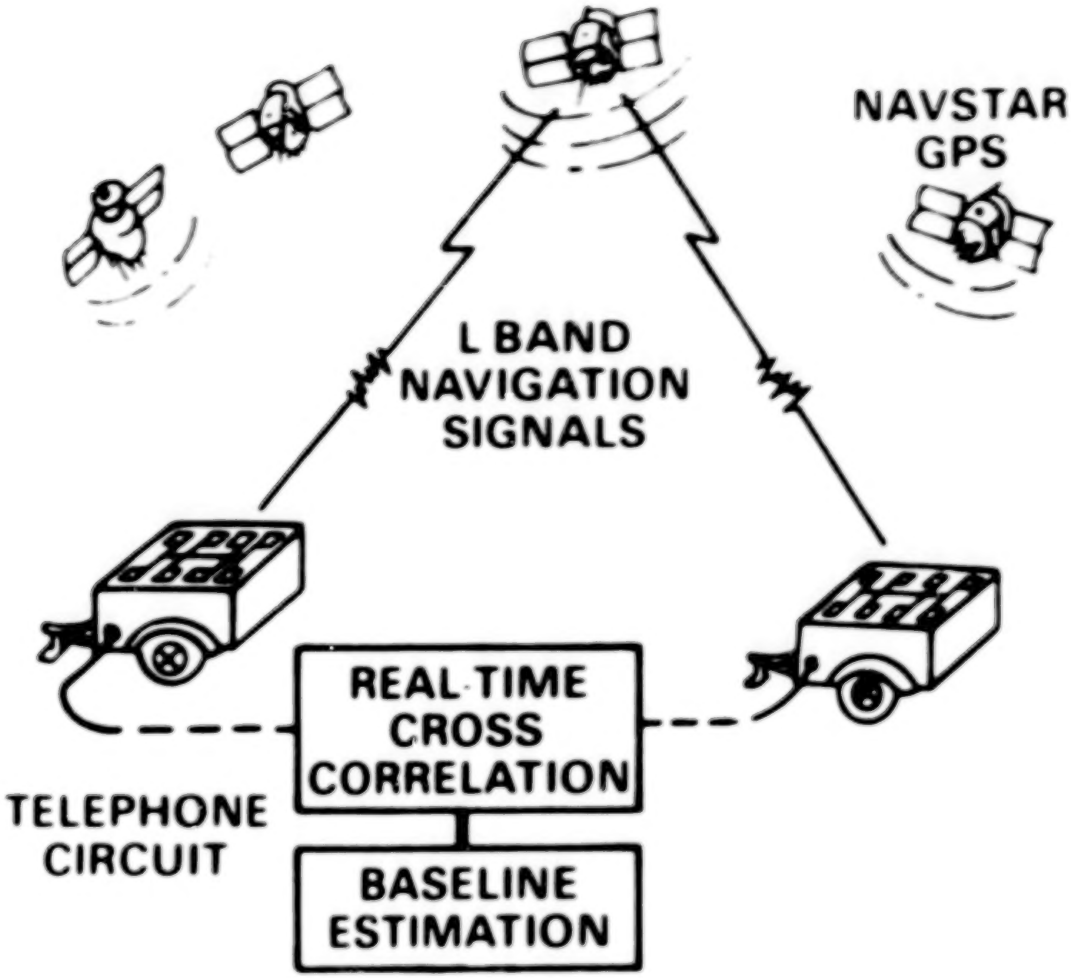


Figure 1. GPS Geodetic Receivers

Geodetic receivers (illustrated here according to the NASA SERIES concept) simultaneously acquire signals from GPS satellites. The system uses one-way differenced range measurements to determine the precise distance between receivers.

BEST COPY AVAILABLE

Five of these ground systems are being constructed for the Crustal Dynamics Project; two are expected to visit sites of tectonic interest while three will occupy fiducial sites for GPS orbit determination.

1.2 Results

The sites which have been, or are planned to be, occupied under the Crustal Dynamics Project are shown in Figure 2.

Preliminary observations of contemporary plate motion generally agree with those averaged over the geological past. Table 1 lists some preliminary results comparing relative rates of motions between the same geometrically determined points as measured using SLR observations using the LAGEOS spacecraft and as determined through geological evidence:

Table 1. Preliminary Observations of Tectonic Plate Movement

	Laser Result*	Geological Record*
North America - Pacific	4 ± 1	2
North America - South America	-1 ± 4	-1
North America - Australia	-1 ± 2	-3
Australia - Pacific	-7 ± 1	-6
Australia - South America	6 ± 3	2
South America - Pacific	5 ± 3	5

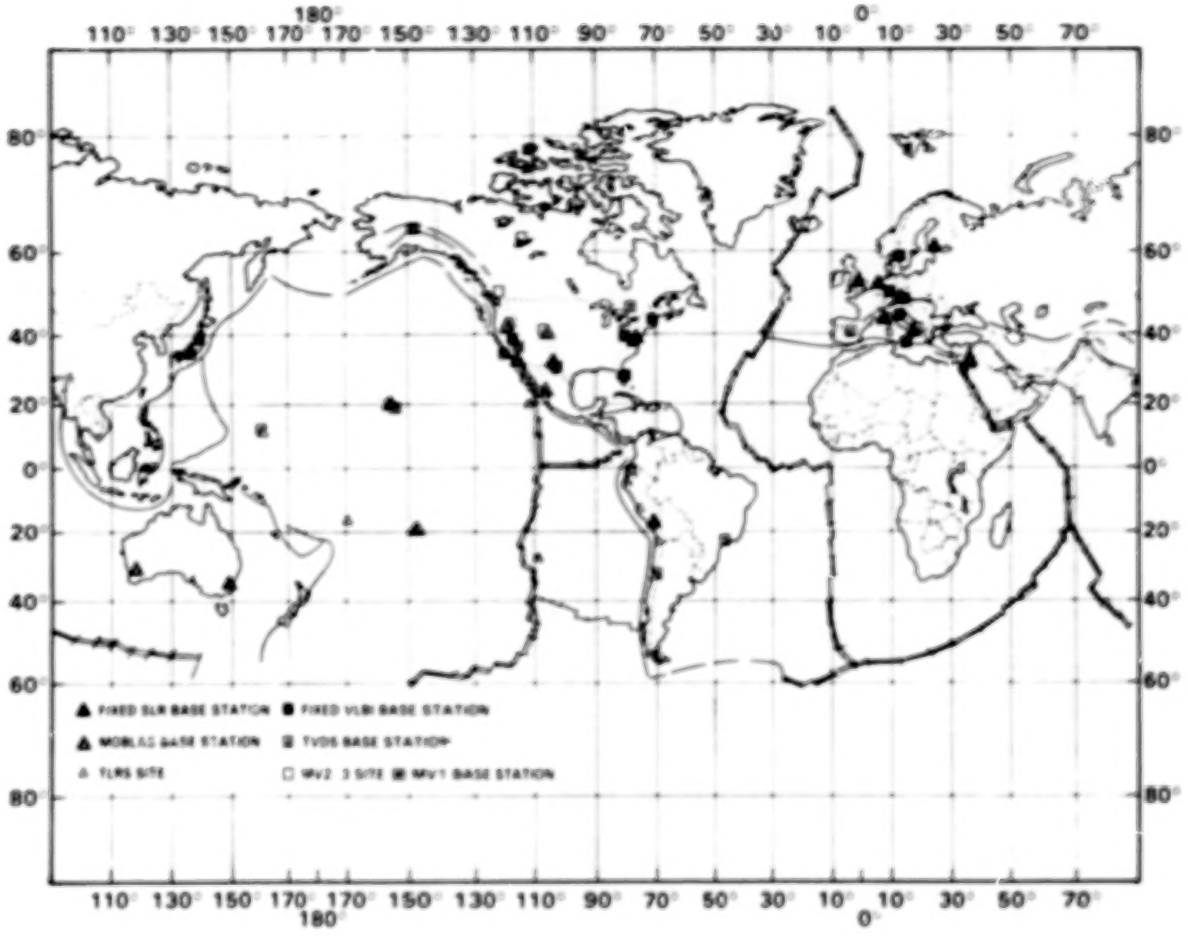
* - cm/year

The results are derived from three years of SLR measurements between specific points on the different plates. VLBI measurements from North America to Europe indicate that this inter-plate distance is increasing at the rate of 1.3 cm/yr. Additional measurements are still needed however, to prove any discrepancy with the movement predicted by plate dynamic models: 1.7 cm/year.

Current results on plate stability are interesting: VLBI measurements have shown that the distance across the North American plate (from Massachusetts to California) is stable to within 0.3 ± 0.24 cm/year. This result uses data acquired since 1976.

By the end of 1983, mobile equipment will have made initial baseline determinations relating to regional deformation in the western U.S. at about 30 different sites.

BEST COPY AVAILABLE


180°
0°
110° 130° 150° 170° 170° 150° 130° 110° 90° 70° 50° 30° 10° 10° 30° 50° 70°
80° 60° 40° 20° 0° 20° 40° 60° 80°
FIXED SLR BASE STATION
FIXED VLBI BASE STATION
MOBILE BASE STATION
TVDS BASE STATION
TLRS SITE
MV2 SITE
MV1 BASE STATION

GLOBAL SITES

Figure 2(A). Crustal Dynamics Project Sites

The geographic locations of Crustal Dynamics Project sites which have been, or will be occupied (according to the site occupation plan in effect in April 1984). The equipment which will occupy these sites is also indicated. A - Global Sites; B - North American Sites; C - California Sites.

BEST COPY AVAILABLE

NORTH AMERICAN SITES

Figure 2(B). Crustal Dynamics Project Sites

BEST COPY AVAILABLE

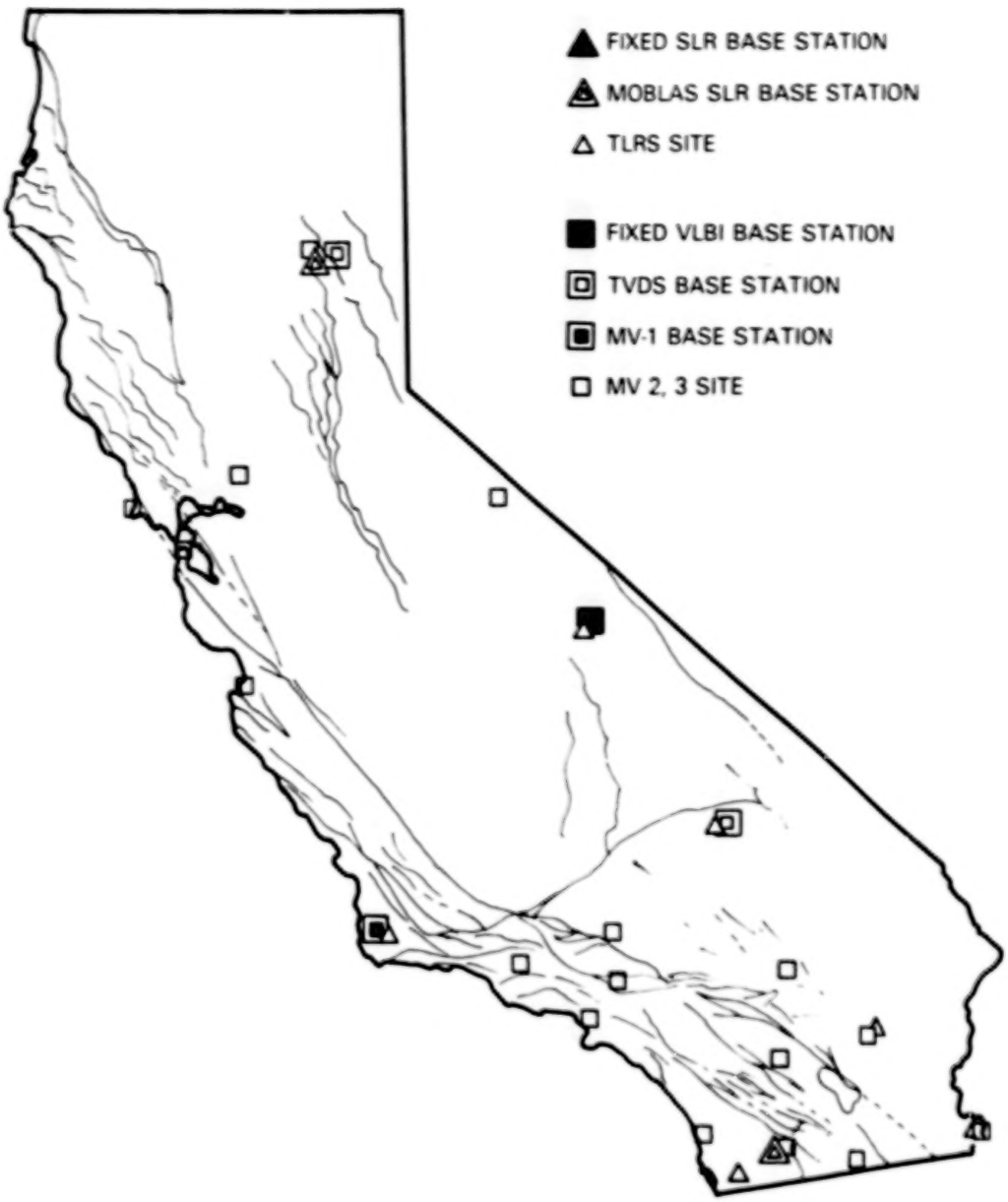


Figure 2(C). Crustal Dynamics Project Sites

BEST COPY AVAILABLE

At the end of the Crustal Dynamics Project in 1988, motions will be determined between the following plate pairs:

North America - Eurasia
North America - Pacific
Nazca - South America
Nazca - Pacific
Australian - Pacific

Epoch measurements and/or approximate determinations of motion will have been made for:

North American - Caribbean
North American - South American
Caribbean - Cocos
Caribbean - South American
Eurasian - Pacific
Aegean - Eurasian
Aegean - African

Assessment of the stabilities of the North American and (western) Eurasian plates will have been made as well as observation of regional deformation in the western U.S. at scales of one centimeter per year.

2. Global Dynamics Measurements

Measurements of the position and motion of the Earth's pole as well as the instantaneous rate of rotation about its axis are derived along with the determination of baseline lengths using VLBI and from the effect these motions have on the position of the independent tracking stations using SLR. The measurements are related, respectively, to an extra-galactic and an earth-centered frame of reference. A third measurement system for earth rotation is provided by lunar laser ranging. The latter technique also permits the study of phenomena relating to lunar libration and tides.

Using these technologies, polar motion has been determined to within 2 to 3 milliarc seconds and variations in rotation period to 20 microseconds. These precisions require about a week of observations but there appears to be important information at shorter time scales. SLR and VLBI measurements agree with each other to within 0.02 milliarc seconds and 0.3 milliseconds.

3. Geopotential Fields

Satellite data have contributed to the mapping of the Earth's gravity field since the earliest satellites were launched. Improved tracking techniques have, correspondingly, contributed to more accurate and more detailed gravity field models under the National Geodetic Satellite

BEST COPY AVAILABLE

Program. These improved techniques involved Doppler- and laser-tracking and, most recently, satellite-to-satellite tracking. In the latter case, 5 by 5 degree anomalies were resolved to ±7 milligals.

Satellite altimetry, from which one can determine the response of the ocean surface (which approximates the geoid) to the gravitational field, has also been used. The Seasat altimeter was able to make such measurements with a precision on the order of ±5 centimeters. The design specification for the TOPEX altimeter height measurement is ±2 centimeters.

The Geopotential Research Mission (GRM) (Figure 3) is planned to advance the knowledge of the gravity field to an accuracy of 1-3 mgal at a spatial resolution of 100 km and the global geoid to an accuracy of ±10 cm at the same resolution. The effect of this spatial/gravity field resolution compared with that of a current GEM model may be noted in Figure 4.

The external magnetic field of the Earth has also been the subject of investigation since the earliest satellites. Much of the early satellite data on the main and crustal fields was provided by the Polar Orbiting Geophysical Observatories (POGO's). Magsat was the first satellite dedicated to the mapping of these fields, carrying both scalar and vector magnetometers at an altitude much lower than the POGO instruments. It has thus been possible to isolate crustal magnetic anomalies on the order of 20 nTeslas despite the fact that they are superimposed on a main field which has a strength of 30,000-60,000 nTeslas. Magsat data have provided an additional dimension in the interpretation of geophysical data in modeling regional geological and tectonic structures (Figure 5). GRM is planned to have an accuracy of 3 nTeslas at a spatial resolution of 100 km.

BEST COPY AVAILABLE

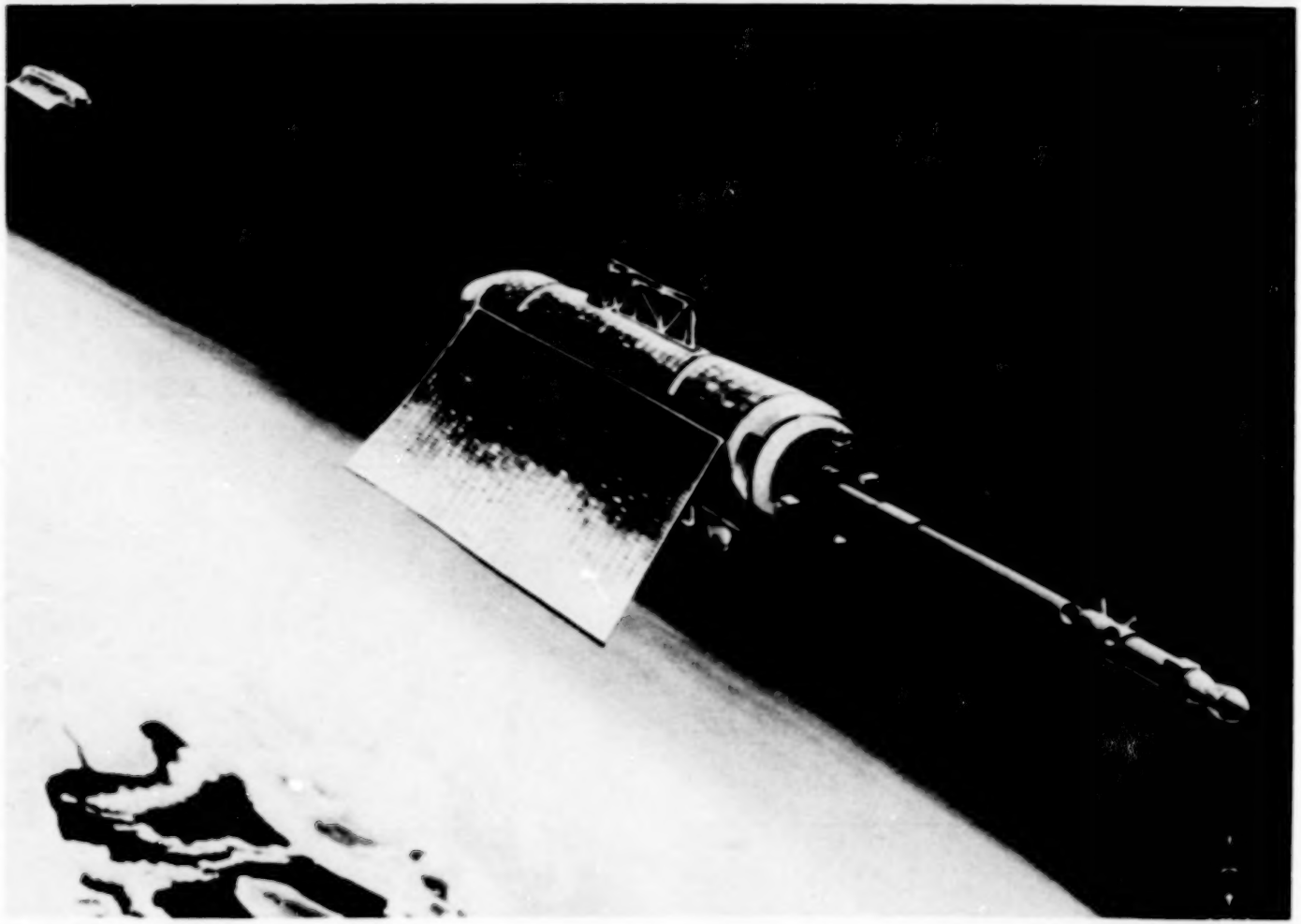
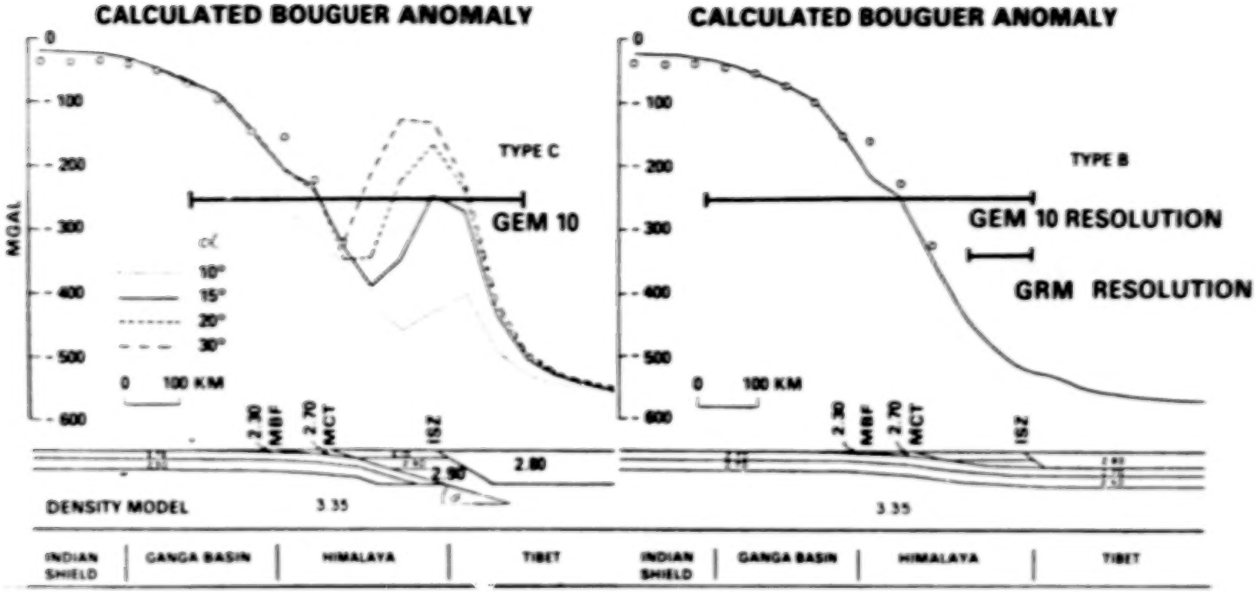


Figure 3. The Geopotential Research Mission

Artist's conception of the satellite system. The distance between stabilized units aboard each of the satellites varies as a function of gravitational heterogeneity beneath the earth's surface. Precise determination of this variation is used to model the gravity field at the surface.

BEST COPY AVAILABLE



- **GRAVITY ANOMALIES OVER THE HIMALAYA WILL INDICATE WHICH UNDERTHRUSTING MODEL IS CORRECT**
- **CURRENT DATA DOES NOT REACH THE CRITICAL AREA**

FROM WARSI AND MOLNAR, 1977

Figure 4. Continent-Continent Collision

Calculated Bouguer anomalies are illustrated for two inherently different models of thrusting of the Indian Shield under the Tibetan Plateau . If precipitous underthrusting of dense layers occurs (model on the left), this may be detected given the spatial and gravity field resolution of the GRM (100 km/ 1-3 mgals). (Warsi, W. E. K., and Molnar, Peter, "Gravity Anomalies and Plate Tectonies in the Himalayas," Colloques Internationaux du C.N.R.S., No. 268, Ecologie et Gelogie de l'Himalaya, C.N.R.S, Paris, 1977)

BEST COPY AVAILABLE

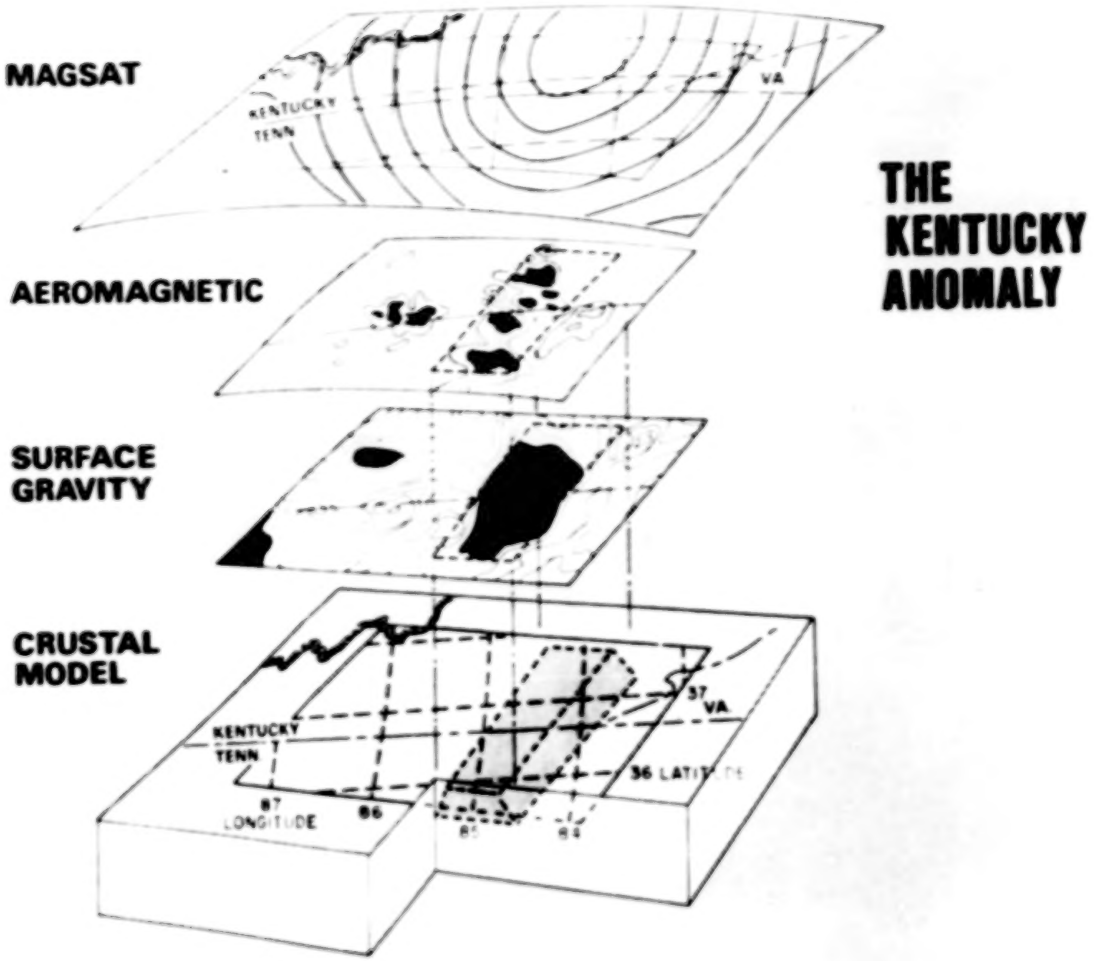


Figure 5. The Kentucky Anomaly

MAGSAT data are used in conjunction with aeromagnetic and surface gravity data in developing a structural model of this enigmatic feature.

BLANK PAGE

III. PROJECTIONS FOR SPACE GEODYNAMICS, 1988-1998

A. Premises

The preceding sections have described the current accomplishments of the Geodynamics Program and those projected through the year 1988. Based on these assessments, and in order to evaluate the directions and requirements for the years beyond, the Geodynamics Workshop established the following set of premises defining the technical and operational environment of the next decade:

1. The Geopotential Research Mission (GRM) will be launched in the early 1990s. Thus, participants could assume the acquisition of data on the Earth's gravity and magnetic fields with observable resolutions of 1-3 mgal and 3 nTeslas respectively at a horizontal spatial resolution, in both cases, of about 100 km.

2. The objectives of the Crustal Dynamics Project will have been attained. Epoch measurements of the relative rates of movement of several major plates (North American, Eurasian, South American, Nazca, Pacific and Australian) will have been determined to an accuracy of 1 cm/year. The internal stability of the North American plate will have been assessed and regional deformation will have been measured in the regions of the San Andreas (1 cm/year), the Aleutian arc (2 cm/year) and the Andes (2 cm/year). (It should be noted that <u>complete</u> deformation measurements in these regions, would require a capability for making precise position measurements on the ocean bottom which will not be available through the Project). Epoch measurements will have been made in the Caribbean and the Mediterranean and other plates.

3. In the United States, most field systems will be operated by operational agencies. Ongoing geodetic surveys, focusing particularly on tectonically-active regions, will be a source of continued data on deformation. In addition, broader-scale fiducial measurements and those relating to satellite orbit determinations will be available operationally to support experimental programs.

4. There will be a global network of fixed VLBI and laser observatories operated largely to fulfill geodetic and astronomical objectives and sanctioned by the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG). These will provide another source of fiducial and orbit data for geophysical measurements on the continental and regional scales. This network should include telemetered broadband seismic instruments.

5. Mobile laser observation systems will have been developed and will be operated by the Federal Republic of Germany, the Netherlands, Japan, Italy and China. The use of these mobile systems will also be internationally coordinated.

BEST COPY AVAILABLE

6. Portable measuring instrumentation based on the use of the Global Positioning System will have been developed and will have demonstrated capability for determining baselines to within 2 cm accuracy over baselines of 2000 km.

B. Results of Panel Discussions

Four panels were organized: Geopotential Fields, Global Dynamics, Tectonics and Regional Tectonics/Crustal Hazards. Within their respective fields of interest, these Panels suggested major questions and proposed the observational programs needed after 1988. The results of these efforts are reviewed in the following paragraphs.

1. Geopotential Fields

The application of geopotential fields to the study of the solid Earth was considered in terms of: (1) the dynamics and structure of the continents, (2) the dynamics and structure of the sub-oceanic crust and lithosphere, and (3) the deep interior including convection in the mantle and the generation of the magnetic field in the core. The Panel also considered the implications of these scientific requirements for future studies, technological developments and missions as well as related applications (e.g., to ocean circulation, the external magnetic field and geodesy).

1.1 Dynamics and Structure of the Continents

Gravity and magnetic measurements from space provide important constraints on the structure, composition, mass distribution and dynamics of Earth. Such data must be investigated over a broad range of spatial wavelengths in order to help separate effects originating at various depths within the Earth. In the case of the magnetic field, it is somewhat easier to differentiate crustal effects from those originating deep in the Earth's interior. The development of geological or tectonic models using gravity field data is improved through the use of topographic data (at commensurate scales).

The Panel discussed in detail a few of the major science needs for which measurements of the geopotential field from space are desirable. These included:

(1) Determination of the degree to which lithospheric flexure and isostasy are associated with supporting various continental structural features. These sources may be differentiated by modelling using gravity and topographic data.

(2) Study of details of the response of the continental crust and lithosphere to the forces (presumably generated by mantle convection) which give rise to features such as collisional mountain ranges, uplifted plateaus, sinking basins and offset

BEST COPY AVAILABLE

faults. The locus of such features often interacts strongly with geologic structures from the past which, in turn, may be perceptible in the gravity data.

(3) Investigation of the strong coupling of positive and negative anomalies which are correlated with mountains in inactive regions such as the Alps and Appalachians. This has been attributed to flexure of the lithosphere at dimensions which would enable estimation of flexure properties using space-derived gravity data.

(4) Modelling of continental rifts and inference of their geologic evolution. Many such rifts probably occur in Precambrian terrain but are hidden by overlying sediments. Such features have important implications for the evolution of continental crust and plate tectonic processes, and may also be the source of valuable minerals. In some cases, they may be detected using a combination of gravity, magnetic and thermal data.

(5) Correlation of tectonic histories between and among continental masses, which, over the eons have been separated, has been investigated by matching of intercontinental geologic structures. Gravity and magnetic field data could contribute to such efforts, especially in modelling.

1.2 Dynamics of the Sub-Oceanic Crust and Lithosphere

While data on the ocean geoid derived from altimetric spacecraft (GEOS-3, Seasat and TOPEX) will have provided a trove of information on sub-oceanic structures and lithosphere, there still will be short wavelength features such as stationary eddies which can distort the apparent gravity field. Surface gravity data at high accuracy and spatial resolution would permit a more detailed investigation of smaller important features such as seamounts, ocean island volcanic accumulations and aseismic ridges and inferences concerning loading, support mechanisms and differentiation histories.

Magnetic data from GRM will be useful, for example, in studying the anomalies associated with the bend in the Hawaii-Emperor Seamount Chain as well as other large anomalies in the western Pacific. Higher resolutions and measurement accuracies would enable detailed study of features of this dimension as well as aseismic ridges, seamount chains and submarine plateaus and would also permit detection of anomalies due to sea floor spreading.

1.3 The Deep Interior

a. The Mantle: Convection and the Gravity Field

The Panel emphasized the fundamental importance of determining the processes which are taking place in the mantle in gaining understanding of its past history, the evolution of the Earth and several basic

BEST COPY AVAILABLE

problems such as the origin of the Earth's atmosphere and the differentiation of its crust. The key problem at this point is the determination of the levels of convection in the mantle: is there one layer, two, or more? Is convection even confined to layers or is it more akin to penetrative or double diffusive convection? Measurements, such as of the gravity field, are needed which can "see" through the lithosphere and into the deeper mantle. Here again, such gravity measurements must be made over a range of spatial scales to permit differentiation of crustal from mantle effects.

While much of the data required would be supplied by the GRM and LAGEOS would continue to contribute to determination of very low degree harmonics ($\ell \leq 4$), a valuable supplement would be provided by a satellite in an intermediate orbit designed to improve the 5-16 degree harmonics of the gravity field. The interpretation of this gravity field should be carried out in the light of improved global seismic data, leading to three-dimensional maps of density variations and flow in the mantle, such as now being provided by seismic topography.

b. The Core: Generation of the Magnetic Field

It seems likely that, in the next decade, major questions will remain concerning the origin of the main magnetic field of the Earth. The prevailing theory is that this field is the result of a dynamo which operates in the Earth's fluid outer core. However, there is no generally accepted cause-and-effect model analogous to that which exists for the Earth's atmosphere. Questions remaining include: What is the topology of this dynamo? What is the source of energy which drives it? What limits the strength of the field at a maximum of about 60,000 nTeslas? Why does the magnetic pole precess and how does this precession vary with time? What causes decay of the main field? As the dipole decays, do higher order terms increase? Is the reversal of the dipole field necessarily associated with increase in the non-dipole terms? Is the variation in the strength of the field correlated with changes in the Earth's rotation? Does this have any effect on the climate?

Satellite data obtained from POGO and Magsat and those to be obtained from GRM have provided, and will continue to provide, snapshot glimpses that will contribute to the solution of these questions. A major contribution, however, would be provided by the launch of a satellite designed for longer life, the "Magnetic Field Explorer". Since the spatial resolution required for main field studies is much less than earlier missions designed primarily to study crustal magnetic anomalies, a high-altitude orbit is adequate. Such a mission would therefore be relatively inexpensive, since sophisticated maneuvering systems for orbit maintenance would not be required. At the same time a network of ground geomagnetic observatories should be set up to facilitate interpretation of the spacecraft data.

BEST COPY AVAILABLE

Data from such a system would measure secular variations in the Earth's field. These can then be extrapolated, along with the field itself, to the core-mantle boundary. The information can then be used to constrain models of the fluid core. The pattern of motion in the top boundary layer of the core is of great interest in unravelling the nature of the dynamo and is also important in forecasting secular variations of the magnetic field. A global network of seismometers, linked by satellite telemetry, can be used to map inhomogeneities in core-mantle boundary topography, thus helping constrain motions in the core.

1.4 Related Applications

The Panel emphasized the necessity of gravity field measurements from GRM for the achievement of the accuracies required in sea surface height measurements by satellite altimetry. The gravity field thus obtained would provide an accurate marine geoid and would allow the TOPEX satellite altimeter data to separate dynamic ocean heights from geoidal undulations. The gravity field improvement also would allow the determination of a more accurate orbit for the TOPEX satellite. Both of these are essential to the determination of the general ocean circulation using altimeter measurements.

The Earth's external magnetic field, which arises from electric currents flowing in the magnetosphere and ionosphere, has been studied using spacecraft data such as from MAGSAT. GRM, at its lower altitude, will provide higher resolution data of the auroral electrojets. It is necessary to model and remove such effects from satellite magnetic data in order to observe the crustal and main fields. However, the temporal changes in the external field permit estimates to be made of the electrical conductivity of the solid Earth because of the induced currents which, in turn, produce secondary magnetic effects observable at satellite altitudes.

The Panel also considered the need for global gravity field measurements for geodetic surveys and, in particular, for the attainment of a global datum for height measurements in order to facilitate tying vertical locations to an equipotential surface. For many applications, global maps of crustal and sediment thickness are required in order to completely model the mantle contribution to the geoid.

1.5 Future Missions and Studies

As a time constraint on missions to study the magnetic field, it should be noted that the utility of such data obtained during the years 1990-1995 would be greatly reduced due to the high solar activity which will occur during that period. Furthermore, if such measurements were delayed beyond 1995, a 15-year time interval after MAGSAT, it is likely that we would fail to observe important, higher-frequency changes in the secular variation. Thus, the acquisition of such data before 1990 is considered to be a high priority.

BEST COPY AVAILABLE

The need for global topographic information in the analysis of both gravity and magnetic field data has been recognized. Satellite imagery of areas to be studied is also desirable. Topographic elevations are needed with an accuracy of a few meters, averaged over an area on the order of the resolution limit of the satellite gravimetric measurements. Some of these data can be provided by existing maps. However, lack of coverage over large areas outside the U.S. dictates the need for a topographic mission designed primarily to obtain elevations over land. Since such data can be acquired relatively quickly and "one-time" data acquisition is satisfactory, low-cost topographic mapping missions exploiting the Space Shuttle may be feasible.

The higher-altitude satellite proposed in the discussion on the deep interior (Section III, Paragraph A) would obtain a new degree of refinement for the longer wavelengths of the gravity field. It may be possible to merge the requirements for this mission with those for a mission to measure long-term variations in the Earth's main magnetic field.

It is likely that, in the future, improvements in our capability to measure the Earth's gravity and magnetic fields will require new types of instrumentation. Gradiometers, both gravity (see Figure 6) and magnetic, may be able to meet these needs, perhaps if they are tethered some 10's of kilometers beneath a low-flying satellite.

Ultimately, the interpretation of the data derived from satellites depends on theoretical insights and computational models. The importance of these aspects in pacing the use of the satellite data and in understanding of the terrestrial phenomena, especially in the deep Earth, should be emphasized.

1.6 The Planets

The Pioneer Venus satellite and recent Soviet missions has revealed the radically different character of the surface of Venus emphasizing the need for topographic and gravity field data of that planet to constrain models of its evolution. Venus is the most nearly Earth-like planet in size and mean density and yet its tectonics appears to be radically different. Because of the high surface temperatures, it may be a model for the early Earth. Topographic and gravity studies of Venus, therefore, are of high priority. More detailed gravity data about the Moon and Mercury would also be valuable.

More detailed magnetometry of the Moon, Mercury and Mars would probably be helpful in unravelling their early histories and relevance to earth history and the origin of the solar system.

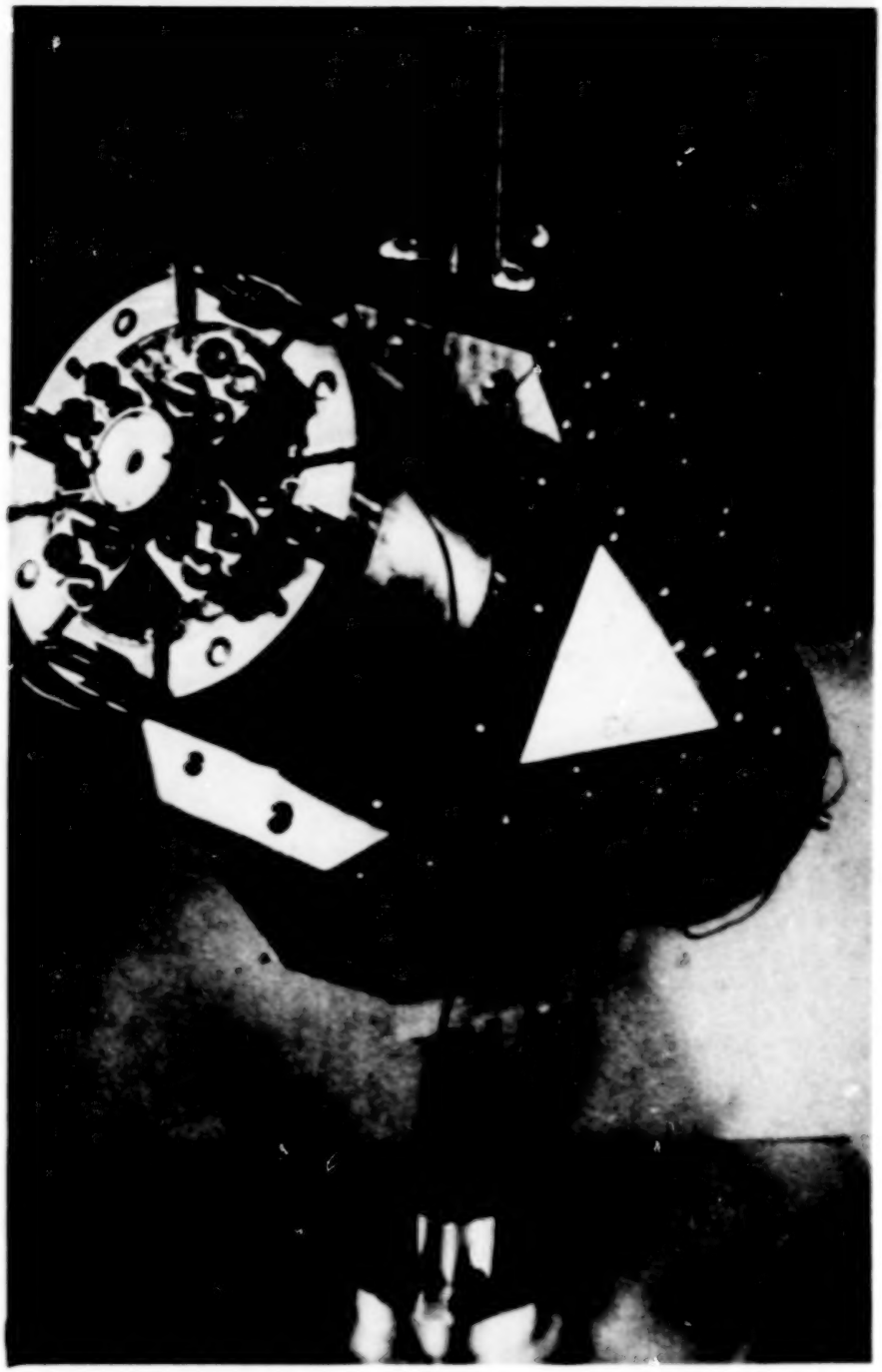


Figure 6. Superconducting Gravity Gradiometer

Photograph of instrument developed by Professor H. J. Paik, University of Maryland. The longest dimension of this instrument is approximately 20 cm. In the laboratory, it is currently capable of detecting changes in the gravity potential of 0.3 ETVOS units per $Hz^{\frac{1}{2}}$. The theroretical limit for this instrument is 0.07 ETVOS units per $Hz^{\frac{1}{2}}$.

BEST COPY AVAILABLE

2. Global Dynamics

2.1 Earth Rotation and Polar Motion

The Earth does not rotate uniformly about its axis. Variations in this motion are categorized as polar motion, nutation and changes in earth rotation rate. The understanding and modelling of these phenomena draw upon and contribute to the fields of meteorology, oceanography, astronomy, celestial mechanics, seismology, tectonics, mantle rheology and dynamo theory. The aim of investigations in the field of global dynamics is to unravel these multi-dimensional effects, thus contributing to all of these fields. It should also be pointed out that accurate measurements of polar motion and earth rotation are also required for precise tectonic motion studies and in navigation to define the frame of reference.

Study of the amplitude and phase of the Earth's nutations enable modelling of the body's elastic and inelastic response. As the agreement between theory and observation in this regard is now better than 0.01" (5×10^{-8}), there is a future need for accuracies better than 0.001" to permit discrimination between various elastic earth models. Study of the damping and excitation of the Chandler wobble will give new information on the inelastic properties of the Earth at long periods, on earthquakes, and on meridional torques due to winds.

Annual and semi-annual variations in the Earth's rotation rate are the result of complex interactions of several phenomena dominated by atmospheric circulation (see Figure 7), although ocean currents and variations in ground water may also play major roles. A higher density of data would be instrumental in unraveling various contributions at higher frequencies. Comparative studies of meteorological models should be pursued. Longer term (i.e., beyond the annual) variations in rotation contain an increasing amount of information on the structure and rheology of the Earth's body, particularly the interaction of the mantle with the fluid core.

2.2 Mission to Map the Time-Varying Gravity Field

It should be possible to measure temporal variations of the gravity field of the Earth through the deployment of several LAGEOS-type satellites, dense radio-beacon satellites, or long lifetime, drag-free satellite(s) using improved laser (or radio)-ranging. It may be necessary to launch these satellites into resonant, or near-resonant orbits to observe changes in the tesseral component of the gravity field. Such satellites could also improve the solution for the variations of the zonal harmonic coefficients by flying in low orbits. This constellation of satellites would be sensitive to variations in the dynamic field caused by seasonal variations in the Earth's water distribution in addition to longer term secular variations caused, for example, by post-glacial rebound.

BEST COPY AVAILABLE

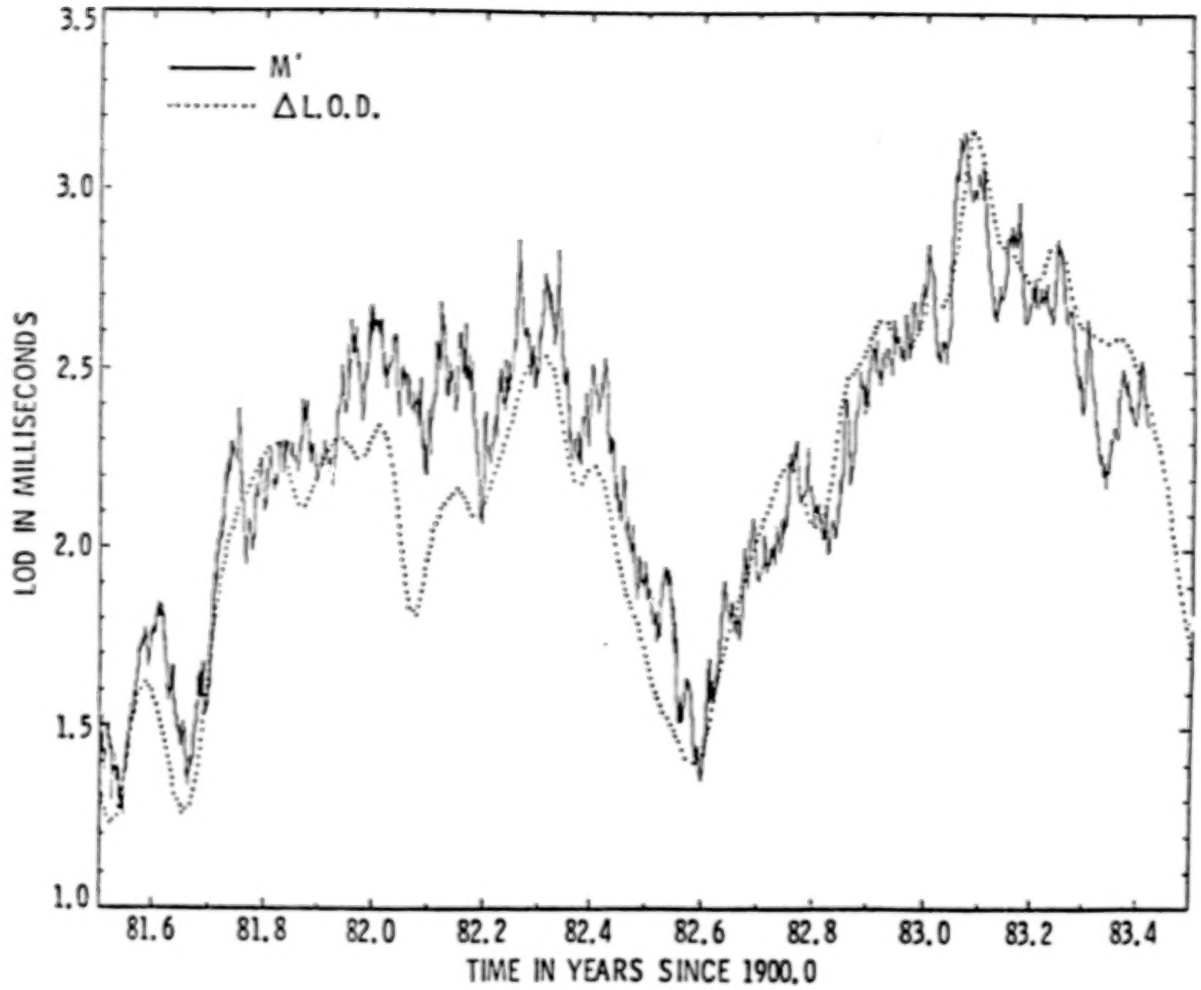


Figure 7. Change in Length of Day

Change in the length of day as determined from BIH data (dotted line) and as calculated on the basis of effects due to changes in the angular momentum of the atmosphere (solid line). (From Rosen, R. D., Salstein, D. A., Eubanks, T. M., Dickey, J. O., and Steppe, J. A. "An El Nino Signal in Atmospheric Angular Momentum and Earth Rotation," submitted to Science, February 1984).

BEST COPY AVAILABLE

2.3 Ground-Based Measurements

Three different techniques are considered: Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR). These refer polar motion and earth rotation to three different reference frames: respectively, distant radio sources, artificial satellite orbits, (which, in turn, are connected to an Earth-centered tracking network) and the Moon's orbit. These reference frames are thus sensitive to different parameters. Consequently, in order to sort out the various effects on the polar motion and Earth rotation phenomena, it is important to sustain all three measurement techniques. The contributions of these systems were considered in terms of three levels of accuracy: decimeter, centimeter and millimeter. The studies which are possible at each of these levels are summarized below.

a. Decimeter Systems

- Ocean/solid body tidal constituents and rate of tidal deceleration of Earth spin and lunar recession.
- Possible determination of the frequency dependence of Q.
- Measurement of forces believed to be dependent on post-glacial rebound and seasonal mass redistributions.
- Measurement of polar motion, possibly to within one or two milliarc seconds which would improve examination of the frequency structure of the Chandler wobble. (Requires improved ability to model atmosphere, oceans and ground water).
- Measurement of the secular drift rate of the rotation pole.
- Possible detection of wobble of the inner core depending on the difference in density between the inner and outer core boundary.
- Detection of polar displacement associated with seismic rupture (earthquakes) and slow earthquakes (pre- or post-seismic rupture). (This technique might be applicable to other planets which rotate slowly).
- Study of the spectrum of Earth rotation variation at periods less than 10 days and its correlation with atmospheric phenomena.

b. Centimeter Systems

Achievement of this level of accuracy is expected before 1988. It will require, for SLR systems, improvements in electronics and internal calibration systems and, for VLBI, deployment of hydrogen masers with stabilities of one part in 10^{15} for periods of a day or less together with corrections for the effects of water vapor.

BEST COPY AVAILABLE

With the achievement of centimeter accuracy, the following capabilities should be possible:

- Determination of the displacement of pole of rotation associated with 7.5 magnitude or greater earthquake.

- Detection of variations in length of day with 0.01 ms/day sensitivity for time intervals as short as five days: required for understanding coupling mechanism of atmospheric winds to earth mantle (friction vs. mountain torques).

- Detection of phase lag in 18.6-year nutation for studying relative motion of inner core, fluid core and mantle.

- Detection of fluid core nutation and/or inner core free nutation.

c. Millimeter Systems

If it is possible to develop systems with millimeter-scale accuracies, using, for example, two color-laser measurements and automated stations, new and difficult observations/studies could be attempted:

- Detection of vertical surface motions associated with tectonic processes.

- Determination of free nutations of the inner and outer cores.

- Determination of spin pole nutation constants allowing constraints on models of internal structures.

- Observation of effects of atmospheric variations on earth rotation rate at time scales of a day, variations of station heights due to ground water fluctuations.

- Detection of wobble of inner core.

3. Tectonics

The need was expressed for data which place constraints on the kinematics and dynamics of tectonic processes (plate tectonics, mountain building, mantle convection and the thermal and geochemical evolution of the Earth). The following specific data types were identified as being needed globally:

- Tectonic velocities of crustal bodies, on all scales, from which strain rates can be derived;

- Gravity;

- Topographic elevations;

BEST COPY AVAILABLE

- Crustal thickness and density in the outer 50 kilometers;

- Seismic velocities in three dimensions, including anisotropy; and

- Stress.

The Panel considered several high-priority questions in tectonics and identified specific measurements and measurement strategies which should be undertaken to provide the data required to answer these questions. Some of these questions require, for their solution, a global network of digital seismometers. Some of the questions and issues are summarized in the following paragraphs.

3.1 Geodetic Measurements

(1) Is the instantaneous plate motion equal to that averaged over the past five million years? Is the motion jerky or smooth? Have there been recent changes in the rates? How spatially uniform across a plate are such motions, i.e., are plates truly rigid?

It is not necessary to make measurements of all plates to provide valuable information. Fast-moving plates should be most sensitive to any variations present. For this reason, additional baselines between Europe and North America are not necessary to answer this question. The following are some high-priority baselines:

Nazca - Pacific
Nazca - South America
Pacific - East Asia
Australia - India - Eurasia
Pacific - North America

Spreading ridges are a <u>critical</u> plate boundary, inasmuch as they may well be the principal surface manifestation of mantle convection. As these are almost entirely sub-oceanic, it would be impossible to obtain adequate data on spreading rates without some capability for determination of relative positions on the ocean floor. The same is true for subduction zones, where islands usually are not located at desirable positions on one side of the plate boundary.

(2) How does motion vary from one plate boundary, across a plate interior, to another plate boundary?

Measurements should be made from a fairly densely spaced network of sites; at 100's of kilometer spacing close to the boundary decreasing to 1000-kilometer centers further away. At convergent boundaries, measurements should be made of rebound

BEST COPY AVAILABLE

following seismic events; therefore, temporal resolution will be important. Measurements should be made every six months far from the fault (+200 km) and closer to the fault on a monthly basis. Possible specific areas for investigation are:

The Aleutians
Japan
Peru

For measurement of the distribution of velocity changes at complicated convergence regions and determination as to whether strain is uniform or discontinuous, the following regions were identified:

Himalayas - Tibet - China
Transverse Ranges of California
The Aegaean
Australia - Borneo - Timor
Iran

And, for the investigation of continental divergence:

The Gulf of California
East Africa - Red Sea - Gulf of Aden
The Rio Grande Rift
The Rhine Graben
Back-Arc Basins

To test whether plate interiors are rigid, measurements on three of them would be sufficient. The following are proposed:

North American Plate (10 stations)
Indo-Australian Plate (two stations in Australia, Sri Lanka and India)
Pacific Plate (six stations on widely distributed islands)

To determine present-day vertical motions, measurement with precision on the order of a millimeter would be needed. Such measurements at long wavelengths (1000 km or more) of post-glacial rebound would be useful in constraining mantle rheology if they were made away from coastlines. Other measurements checking features of the Earth's geoid should be made in Sri Lanka, the western Pacific, Siberia, Ross Island and southwestern California.

Vertical measurements at shorter wavelengths should be made of tectonically active areas such as:

The Himalayas
Southern California
The Basin and Range Province, U.S.

BEST COPY AVAILABLE

Other measurements should be made in mountainous regions which appear to be relatively inactive, such as:

The Adirondacks
The Appalachians

3.2 Gravity Data

Gravity data provide fundamental insights into the dynamics of the Earth, particularly on the following:

- The pattern of mantle convecting system and the variation of its rheology with depth and laterally. Models require knowledge of surface deformation or a priori knowledge of the sign, approximate magnitude and location of the density contrasts such as can be provided using seismic techniques.

- The dynamics of mountain building. To observe critical regions, gravity data are required at resolutions better than 2 mgal and 100 km.

- The detection, if present, of convection unassociated with plate motion.

3.3 Information/Measurement Requirements

The Panel specifically identified the following needs for information and coordination:

- Development of an ocean floor positioning system.

- Development of GPS receivers enabling spatially and temporally abundant geodetic measurements.

- Deployment of seismometers and magnetometers in conjunction with the prescribed geodetic measurements.

- Mapping of global topography.

- Determination of vertical movements with accuracy of millimeters/year.

- Better computers and improved algorithms for data analysis and modelling.

- Global tidal sea level patterns for correcting ocean loading parameters.

BEST COPY AVAILABLE

4. Regional Tectonics - Crustal Hazards

Many important questions concerning tectonic motions exist - and will probably persist into the next decade. Perhaps the most fundamental of these relates to the accumulation and dissipation of strain at plate margins. This, in turn, involves the rheology of the crust and the forces which drive the plates, the nature of the boundaries of the plates and their breakup into microplates. It is also important to answer these questions in order to gain understanding of earthquake mechanisms especially so that their occurrence may be more reliably predicted. They also relate to other hazardous phenomena such as volcanism, subsidence and uplift as well as to applications such as resource exploration and surveying.

The Panel considered the question of making the basic geodetic measurements which can be related to strain accumulation and dissipation and developed the summary of current and projected measurement system capabilities which appears in Table 2. It also developed priorities for the location of such measurements and recommended spatial and temporal densities for the observation campaigns.

4.1 Regions of Interest

The region identified as having the highest priority for such measurements was the western United States. This region has a relatively simple tectonic framework, a large body of existing relevent knowledge and is the focus for many complementary observations (such as satellite imagery, conventional ground-based surveys and seismic arrays). It is, perhaps most importantly, an area which is susceptible to large, extremely damaging earthquakes. The Pacific Northwest has recently been identified as the potential site of very large, subduction-related earthquakes. Idaho recently had a major normal event which focuses attention on the Basin and Range region.

The subduction zone of western Alaska was next noted because it, too, is highly susceptible to earthquakes. Indeed, two seismic gaps - Shumagin and Yakataga - have been identified in the region. Other observation programs, notably seismic, are being conducted there.

Other major seismic areas in order of priority are:

North Anatolian Fault (Turkey)
Alpine Fault (New Zealand)
Andes (Central, South America)
Tonga-Fiji - Kermadec-New Zealand Region
Caribbean
Mediterranean

BEST COPY AVAILABLE

TABLE 2. ACCURACY ESTIMATES FOR 400 KM BASELINES

SYSTEM	PRESENT CAPABILILTY HOR(cm)	VERT(cm)	1988 (PROBABLE) HOR(cm)	VERT(cm)	1990s (POSSIBLY ACHIEVABLE) HOR(cm)	VERT(cm)	DATA ACQUISITION TIME
GPS			1	2	0.5	0.8	1 hour
VLBI	1.4-2	4-5	1	2	0.3	0.5	1 day
LASER	3	3	1	1	0.5	0.3	1 week
SINGLE COLOR GEODIMETER	1 (50km)	-	1 (50km)	-	1 (50km)	-	1 hour
MULTI-COLOR GEODIMETER	0.2 (10km)	-	0.3 (30km)	-	0.3 (50km)	-	1 hour
OCEAN BOTTOM TIE	100	100	10	10	3	3	1 hour
AIRBORNE LASER	-	-	-	-	1	2	1 hour
SATELLITE PLATFORM LASER	-	-	-	-	1	1	3 days (50km net)
IMPROVED GPS	-	-	-	-	0.3	0.5	1 hour

BEST COPY AVAILABLE

In many of these areas, earthquakes are more frequent than in the western U.S. Thus, they can provide more information and a basis for comparison since they have some features in common with Alaska and the U.S. Pacific coast.

A program of observations was also recommended for the eastern United States where the low rates of movement would necessitate an observational capability with precision of one to three millimeters (horizontal and vertical) over 100 to 200 kilometer baselines.

4.2 Observational Program Requirements - Western U.S.

Only the observational requirements for the highest priority area - the western United States - were detailed. Three aspects were considered: (1) secular strain accumulation, (2) co- and post-seismic studies of deformation, and (3) earthquake prediction.

a. Determination of Secular Strain Accumulation Patterns

Every one or two years, the USGS Trilateration Networks provide data with one centimeter precision on 1000 baselines, each 10-30 km in length, in the western U.S. These data may be combined with leveling data (five lines in southern California) and gravity observations (about 40 sites) and Crustal Dynamics Project data (over 25 stations per year).

The current observation strategy, however, could be greatly improved by providing: (1) measurements of vertical displacements, (2) a regional framework to which to tie local observations, and (3) geodetic control of deformation to the west of the San Andreas fault, particularly north of San Francisco.

The Panel recommended the establishment of a network of about 30 stations at 100 km spacing covering the area 100 kilometers to either side of the San Andreas for observation in both vertical and horizontal dimensions at an accuracy of one centimeter with observations made one or two times a year. This would require development of a capability for making geodetic measurements from points on the ocean bottom off the California coast in which case, because of the absence of other data, measurements with 5-cm accuracy, even if made every ten years, would yield useful information.

In addition, a network of stations with approximately 500 kilometer spacing covering the entire active portion of the western U.S. with horizontal and vertical positional observations of one cm accuracy is needed.

b. Co-Seismic and Post-Seismic Studies of Deformation

These observations were recommended because earthquakes provide unique opportunities to study the rheology of the lithosphere and the horizontal and vertical distribution of the relative motion at plate

BEST COPY AVAILABLE

boundaries. These measurements should commence within days after an earthquake and continue for some months. Two complementary strategies should be pursued:

(1) Daily or continuous observations at perhaps 20 sites at distances from 0 to 50 km from the fault and distributed along the rupture or aftershock zone. Co-seismic observations require a 1-cm accuracy; post-seismic observations require an accuracy of 1-3 mm.

(2) Observation of horizontal and vertical movements at 25 to 50 km spacing at distances ranging to 200 km from the fault, repeated every three months until deformation ceases. An accuracy of 1-3 mm will be required, particularly at large distances and times from the event.

c. Earthquake Prediction

For application to the problem of earthquake prediction, geodetic techniques must be able to provide frequent measurements with high accuracy over large total areas. Because the size of the signal is unknown, measurements of the highest accuracy are required.

IV. RECOMMENDED PROGRAM ACTIVITIES, 1988-1998

A. Ground-Based Observations

Programs of ground-based SLR, LLR, and VLBI measurements are recommended to study earth rotation and polar motion, to assess the constancy of plate motion, to determine the rates of intra-plate deformation and uplift, and to study deformation on regional and local scales. The details of these requirements have been presented in the previous Section of this report (Section III. B.).

Many of the future needs require no augmentation of current technical capability. Long-term monitoring of plate motion to determine whether the relative velocities are constant with time could be achieved with the technology available at the close of the Crustal Dynamics Project. The same techniques could also be used for some of the recommended studies of plate rigidity and continental divergence. At the same time, measurements with 1-cm accuracy could satisfy many of the requirements relative to polar motion and Earth rotation changes over longer time intervals.

Determination of shorter baselines for studies of regional deformation and especially those requiring frequent measurements as in the case of co-seismic and post-seismic deformation studies as well as frequent (e.g., daily) determinations of Earth rotation and polar motion will probably require additional capabilities. For the baseline measurements, these could be provided by the continued development and deployment of GPS receivers using the current and presently projected array of GPS satellites. In this case, technical developments would involve improved methods for taking into account atmospheric effects (e.g., better water vapor radiometers) and improved satellite orbit determinations.

Studies of the optimum deployment of the GPS receivers in a program of dense, frequent measurements in the 1990s should be undertaken to determine the cost effectiveness of a separate GPS-type satellite system specifically designed for use in geodynamics. Such a system would be relatively inexpensive, consisting of a few satellites (five or six) transmitting multiple-tone signals for precise and rapid position determinations.

Yet denser and more frequent observation programs will probably require the development of Airborne or Spaceborne Laser Ranging Systems. Such systems would be used to determine baseline lengths between corner cube reflectors located in a densified array at fixed locations on the ground. Theoretical studies have thus far shown that such systems are feasible, however, engineering tests should be carried out to determine operational limits and system costs.

BEST COPY

The nature of plate motion is such that many of the important and interesting boundaries occur near the land-ocean interfaces. Thus, for observation programs at several important plate boundaries (e.g., western U.S., the Aleutians, Japan and Peru), technology is needed which would enable measurement of baselines one end of which is under the ocean. A similar situation exists at most divergent plate boundaries (mid-ocean spreading centers). In most of these cases, suitable land exposures are not available for making positional determinations: both ends of the baseline for measuring spreading rates will most likely be under the ocean. One of the concepts for making such measurements is illustrated in Figure 8. The specific requirements and approaches to technical implementation of a sub-oceanic positioning system have been discussed in some detail in a recent study of the National Research Council (Seafloor Referenced Positioning: Needs and Opportunities, National Academy Press, Washington, D.C., 1983). While recognizing the technical difficulties, the report notes several major benefits provided and mentions several possible approaches through which positions on the ocean bottom could be referenced to instrumentation at the ocean surface which, in turn, could be used for positioning. In view of the paucity of data at such boundaries, positional measurements would be useful even though provided infrequently (every few years) and at relatively low levels of accuracy (e.g., five centimeters).

Another technical challenge will be the determination of the vertical components of baselines to the recommended accuracy on the order of millimeters. Such determinations are needed relatively frequently on short baselines to study local uplift in conjunction with dilatancy and less frequently on longer baselines to study regional uplift, particularly in inactive regions such as the Adirondacks. To make such measurements would require a finely tuned observation system, one which had the capability to monitor and correct for even small variations in the index of electromagnetic wave refraction in the atmosphere due to changes in its chemical and physical properties.

B. Space Missions

In the preceding section, several space missions have already been proposed to support ground-based measurements. One consideration is the possibility that constellation of GPS-type satellites dedicated to the support of the civilian geodynamics program could facilitate significantly frequent regional positional determinations. The Airborne or Spaceborne Laser Ranging Systems could provide a practical method for making frequent positional measurements of a high-density array of point for studies of local deformation. A more economical but less satisfactory alternative would be to place a second satellite similar to LAGEOS in orbit to shorten the observation time required by mobile SLR systems.

It is recommended that satellites designed to measure gravity field variations at very long wavelengths be considered in order to permit observation of changes in the Earth's gravity field at these

BEST COPY AVAILABLE

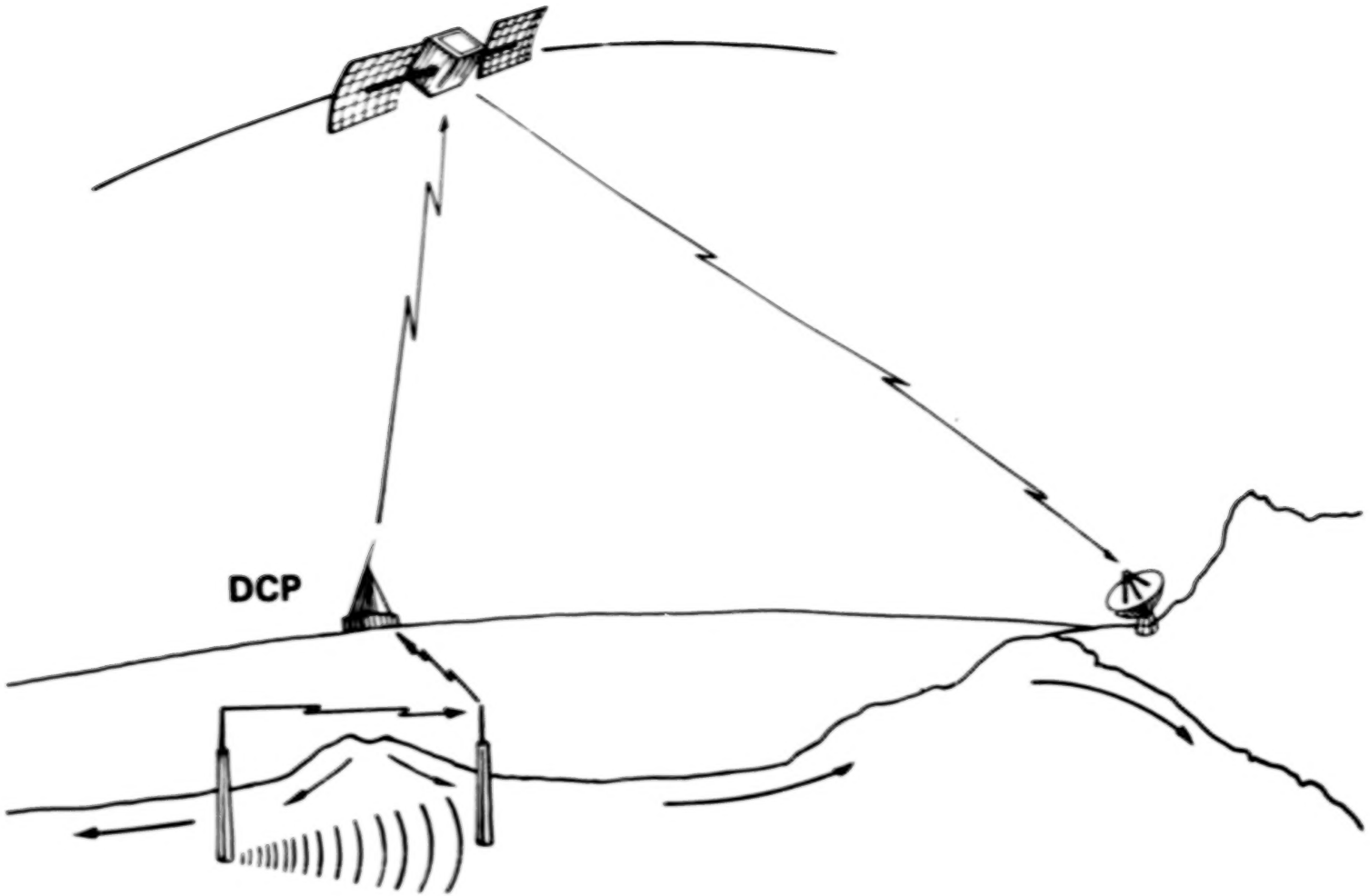


Figure 8. Concept for Monitoring Ocean Floor Spreading

One concept for measuring relative distances between sub-oceanic sites (in this case, on opposite sides of a spreading center) and to land is illustrated here. Acoustic position measurement is used through water to establish positions relative to a Data Collection Platform (DCP). The position of the DCP is determined relative to a ground station using the Global Positioning System satellite.

BEST COPY AVAILABLE

wavelengths. This could be achieved by launching one or more very dense or drag-free satellites perhaps similar to LAGEOS, into appropriate orbits.

An important contribution to the understanding of the dynamics of the core and modelling of the Earth's magnetic field could be made by a high-altitude (several Earth radii) satellite capable of monitoring the main magnetic field for extended periods of time - up to a decade. Such monitoring is necessary in order to allow global observation of changes in the secular variation of the field which can be related to changes in the dynamo.

A current impediment to the full use of magnetic and, especially, gravity field data is the deficiency of accurate global topographic information. It is recommended that an effort be made to acquire a global set of this information. A significant contribution could be made by data averaged over 1-10 km and with relative precision of 5 meters. The data could be acquired with a suitably designed microwave or scanning laser altimeter aboard the Space Shuttle or other appropriate space platform.

C. Instrument Development

To provide sensitivities to short wavelengths, both gravity and magnetic gradiometers should be developed.

Continued development of the Airborne and Space-Borne Laser Ranging Systems should be supported.

To support the ground-based measurement program, and in particular the requirement for millimeter accuracy in both the horizontal and vertical components, instruments should be developed for determining and/or eliminating the effects of the atmosphere.

D. Ancillary Measurements and Supporting Activities

It is noted that any measurements of the magnetic field by satellite should be carried out in conjunction with a strong program of contemporaneous ground-based measurements of the magnetic field. The existing global network of stations should be operated and coordinated with the satellite operations so temporal variations during the satellite epoch can be logged.

Baseline measurements, particularly in the western U.S., should be conducted in conjunction with, and in support of, local and regional networks in which baseline and tilt are measured in conjunction with earthquake prediction studies. Furthermore, such geodetic measurements should be supported by the acquisition of appropriate seismic data. The determination of vertical displacements is somewhat sensitive to tidal effects, especially ocean loading. Such measurement programs should be supported by monitoring of sea levels.

BEST COPY AVAILABLE

The development of algorithms and models in the application of space data in geodynamics should be given special attention. The full analysis of data obtained from the GRM should be supported, and adequate computer support to perform this task should be provided.

BEST COPY AVAILABLE

APPENDIX I

GEODYNAMICS WORKSHOP ATTENDEES
AIRLIE HOUSE
AIRLIE, VIRGINIA

February 15-18, 1983

Dr. Arden L. Albee
Division of Geological and
Planetary Sciences
California Institute of Technology
Pasadena, CA 91125
FTS-792-6057

Dr. Don L. Anderson
Sesmological Laboratory
California Institute of Technology
Pasadena, CA 91125
213/356-6901

Dr. Peter L. Bender
Joint Institute for Laboratory
Astrophysics
University of Colorado
Boulder, CO 80309
303/492-6793
FTS-320-3846 or -3151

Dr. Edward R. Benton
Campus Box 391
Department of Astro-Geophysics
University of Colorado
Boulder, CO 80309
303/492-7988 or -8913

Mr. John M. Bosworth
NASA/Goddard Space Flight Center
Code 904
Greenbelt, MD 20771
301/344-7052

Dr. Kevin C. Burke
Department of Geological Sciences
State University of New York
Albany, NY 12201
713/486-2138

Dr. William E. Carter
NOAA/National Ocean Survey
National Geodetic Survey, C-12
6100 Executive Boulevard
Rockville, MD 20842
301/443-8423 or -8171

Dr. Clem Chase
Department of Geology & Geophysics
University of Minnesota
Minneapolis, MN 55455
612/373-5070

Dr. Demos Christodoulidis
NASA/Goddard Space Flight Center
Code 921
Greenbelt, MD 20771

Dr. Thomas A. Clark
NASA/Goddard Space Flight Center
Code 974
Greenbelt, MD 20771
301/344-5957

Dr. Robert J. Coates
NASA/Goddard Space Flight Center
Code 921
Greenbelt, MD 20771
301/344-8809

Dr. Steven C. Cohen
NASA/Goddard Space Flight Center
Code 921
Greenbelt, MD 20771
301/344-7641

Dr. John M. Davidson
Jet Propulsion Laboratory
Mail Stop 264-748
4800 Oak Grove Drive
Pasadena, CA 91109
FTS-792-7508

Dr. John Degnan
NASA/Goddard Space Flight Center
Code 723.2
Greenbelt, MD 20771
301/344-7714

BEST COPY AVAILABLE

Dr. Timothy H. Dixon
Jet Propulsion Laboratory
Mail Stop 183-701
4800 Oak Grove Drive
Pasadena, CA 91109
FTS-792-4977

Mr. Bruce C. Douglas
NOAA/National Geodetic Survey
Code C-12
Rockville, MD 20852
301/443-8858

Dr. Adam Dziewonski
Department of Geological Sciences
Harvard University
20 Oxford Street
Cambridge, MA 02138
617/495-2510

Dr. John Fanselow
Jet Propulsion Laboratory
Mail Stop 264-748
4800 Oak Grove Drive
Pasadena, CA 91109
FTS-792-0323

Mr. Charles J. Finley
NASA Headquarters
Code EE
Washington, DC 20546
202/453-1675

Mr. Thomas L. Fischetti
NASA Headquarters
Code EE
Washington, DC 20546
202/453-1675

Dr. Edward A. Flinn
NASA Headquarters
Code EE
Washington, DC 20546
202/453-1675

Dr. Herbert Frey
NASA/Goddard Space Flight Center
Code 922
Greenbelt, MD 20771
301/344-5450

Dr. E. Michael Gaposchkin
Group 92 Millstone
Massachusetts Institute of
Technology
Lincoln Laboratories
P.O. Box 73
Lexington, MA 02173
617/863-5500 x5664
617/862-4426 (home office)

Dr. Bradford Hager
Seismological Laboratory
California Institute of Technology
Pasadena, CA 91125
213/356-6938

Dr. Christopher G.A. Harrison
RSMAS
Univeristy of Miami
4600 Rickenbacker Causeway
Miami, FL 31149
305/350-7400

Dr. Sigmund W. Hieber
8-10 Rue Mario Nikis
F-75738 Paris
Cedex 15
FRANCE
567-55-78

Mr. Werner D. Kahn
NASA/Goddard Space Flight Center
Code 921
Greenbelt, MD 20771
301/344-5462

Professor William M. Kaula
Institute of Geophysics
& Planetary Physics
University of California
Los Angeles, CA 90024
213/825-4363 or -1919

BEST COPY AVAILABLE

Dr. Robert A. Langel
NASA/Goddard Space Flight Center
Code 921
Greenbelt, MD 20771
301/344-6565

Dr. Mark M. Macomber
Deputy Director, Systems & Technique
Building 56
Defense Mapping Agency
Washington, DC 20305
202/653-1426

Mr. James G. Marsh
NASA/Goddard Space Flight Center
Code 921
Greenbelt, MD 20771
301/344-5324

Dr. D. C. McAdoo
NASA/Goddard Space Flight Center
Code 921
Greenbelt, MD 20771
301/344-6120

Dr. William G. Melbourne
Jet propulsion Laboratory
Mail Stop 238-540
4800 Oak Grove Drive
Pasadena, CA 91109
FTS-792-5071

Dr. Peter Molnar
Department of Earth & Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139
FTS-835-5924
617-253-5924

Dr. W. Jason Morgan
Department of Geological & Geophysical Sciences
Princeton University
Princeton, NJ 08540
609/452-3596

Professor Ivan I. Mueller
Department of Geodetic Science & Surveying
Ohio State University
1958 Neil Avenue
Columbus, OH 43210
614/422-2269

Mr. James P. Murphy
NASA Headquarters
Code EE
Washington, DC 20546
202/453-1675

Dr. William L. Piotrowski
NASA Headquarters
Code EL
Washington, DC 20546
202/453-1603

Mr. William H. Prescott
Office of Earthquake Studies
U.S. Geological Survey, MS 77
345 Middlefield Road
Menlo Park, CA 94127
415/323-8111 x2701

Dr. Richard H. Rapp
Department of Geodetic Science & Surveying
Ohio State University
1958 Neil Avenue
Columbus, Ohio 43210
614/422-6005

Mr. Courtney Ray
The Johns Hopkins University
Applied Physics Laboratory
John Hopkins Road
Laurel, MD 20707
301/953-7100

Dr. Nicholas Renzetti
Jet Propulsion Laboratory
Mail Stop 264-802
4800 Oak Grove Drive
Pasadena, CA 91109
FTS-792-4518

BEST COPY AVAILABLE

Dr. R. Steven Saunders
Jet Propulsion Laboratory
Mail Stop 183-501
4800 Oak Grove Drive
Pasadena, CA 91109
FTS-792-3815 or -2046

Dr. Irwin I. Shapiro
Perkin 209
Harvard College Observatory
Harvard University
Cambridge, MA 02138
617495-7100

Dr. Peter J. Shelus
Department of Astronomy
McDonald Observatory
University of Texas at Austin
RLM 15.316
Autin, TX 78712
512/471-4461

Mr. William L. Sjogren
Jet Propulsion Laboratory
Mail Stop 264-664
4800 Oak Grove Drive
Pasadena, CA 91109
FTS-792-4868

Dr. David E. Smith
NASA/Goddard Space Flight Center
Geodynamics Branch, Code 921
Greenbelt, MD 20771
301/344-8555

Dr. Fred Noel Spiess
Institute of Marine Resources,
A-028
Scripps Insitution of Oceanography
University of California at
San Diego
La Jolla, CA 92093
619/452-2866

Mr. Donald W. Trask
Jet Propulsion Laboratory
Mail Stop 264-720
4800 Oak Grove Drive
Pasadena, CA 91109
FTS-792-4878

Dr. Donald L. Turcotte
Department of Geological Sciences
Cornell University
210 Kimball Hall
Ithaca, NY 14853
607/256-7282

Dr. F.O. Von Bun
NASA/Goddard Space Flight Center
Code 900
Greenbelt, MD 20771
301/344-5201
202/755-1201 (NASA HQ)

Ms. Karen S. Wallace
Jet Propulsion Laboratory
Mail Stop 264-7248
4800 Oak Grove Drive
Pasadena, CA 911009
FTS-792-4552

Dr. Anthony B. Watts
Lamont-Doherty Geological
Observatory
Palisades, NY 10964
914/359-2900 x350

Dr. Charles F. Yoder
Jet Propulsion Laboratory
Mail Stop 264-781
4800 Oak Grove Drive
Pasadena, CA 91109
FTS-792-2444

Mr. Thomas W. Zagwodski
NASA/Goddard Space Flight Center
Mail Code 123.2
Greenbelt, MD 20771
301/344-5020

53 BEST COPY AVAILABLE

APPENDIX II

GEODYNAMICS WORKSHOP AGENDA

FEBRUARY 15

9:00 - 10:00	SESSION I: Keynote	CHAIRMAN: Fischetti
	- Welcome	- Flinn
	- Outlook for NASA Geodynamics Programs	- Briggs
	- Workshop Plans and Expections	- Fischetti
10:00 - 12:30	SESSION I: Science	CHAIRMAN: Flinn REPORTER: Frey
	(Where are we? Where do we expect to be by 1990?)	
2:30 - 6:00	SESSION III: Science	CHAIRMAN: Burke REPORTER: Cohen
	(What are the key questions for the next decade?)	
6:00 - 7:00	Cash Bar	

FEBRUARY 16

9:00 - 12:30	SESSION IV: Technology	CHAIRMAN: Coates/Smith REPORTER: Davidson
	(Where are we now? Where do we expect to be by 1990?)	
1:30 - 4:00	SESSION V: Technology	CHAIRMAN: Bender REPORTER: Kahn
	(What is the outlook for the future?)	
7:30 - 11:00 (PM)	SESSION VI: Programmatics	CHAIRMAN: Fischetti REPORTER: Murphy
	• NASA Role Versus Other Agencies	- Carter
	• JPL Role. Post 1985	- Melbourne
	• International Balance	- Flinn
	• GRM New Start Strategy	- Murphy
	• Support of Adv. Technology	- Piotrowski
	• Relation to Other Program Areas Oceans, Atmospheres, and Climate	- Hudson

BEST COPY AVAILABLE

GEODYNAMICS WORKSHOP AGENDA (CONT'D)

FEBRUARY 17

9:00 - 12:30	SESSION VII: Future Program Thrusts (General Discussion - Program Areas, Needs Opportunities, Capabilities)	CHAIRMAN: Flinn
1:30 - ?	SESSION VIII: Panel Discussions	
	(Proposed Programs, Study and Technology Needs)	
	Panels:	
	A. Tectonics	- Hager
	B. Crustal Hazards	- Prescott
	C. Solid Body Dynamics	- Yoder
	D. Potential Fields	- Kaula
6:00 - 7:00	Cash Bar	

FEBRUARY 18

9:00 - 12:30	SESSION IX: Panel Reports	PANEL CHAIRMEN REPORTER: Wallace
2:00 - 4:00	Session X: Program Opportunities	CHAIRMAN: Fischetti
	(1985 - 1995), (Objectives, Schedules, Priorities)	
4:00 - Adjourn		

BEST COPY AVAILABLE

1. Report No. NASA CP-2325	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle GEODYNAMICS		5. Report Date July 1984 6. Performing Organization Code EE
7. Author(s) L. S. Walter		8. Performing Organization Report No.
9. Performing Organization Name and Address Earth Science and Applications Division NASA Office of Space Science and Applications Washington, DC 20546		10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Conference Publication 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This document summarizes the discussions, results and recommendations of the Geodynamics Workshop which was held at the Airlie House, Airlie, Virginia in February 1983. The Workshop had two objectives: (1) to evaluate the scientific and technological progress expected to be achieved in NASA's Geodynamics Program by 1988, and (2) to recommend activities needed to address the important geodynamics research needs of the next decade.

17. Key Words (Suggested by Author(s))	18. Distribution Statement		
Geodynamics, Crustal Dynamics, Tectonics, Magnetic Fields, Gravity Fields, Geodesy, Laser Ranging, VLBI, Earthquakes	Unclassified - Unlimited Subject Category 42		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 66	22. Price A04

For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1984

BEST COPY AVAILABLE

10-2-84